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WIND-TUNNEL TESTS OF A 2-ENGINE AIRPLANE MODEL AS A PRELIMINARY STUDY OF FLIGHT CONDITIONS ARISING ON THE FAILURE OF ONE ENGINE

By Edwin P. Hartman

SUMMARY

Wind-tunnel tests of a 15-foot-span model of a 2-engine low-wing transport airplane were made as a preliminary study of the emergency arising upon the failure of one engine in flight. Two methods of reducing the initial yawing moment resulting from the failure of one engine were investigated and the equilibrium conditions were explored for two basic modes of flight on one engine, one with zero angle of sideslip and the other with several degrees of sideslip. The added drag resulting from the unsymmetrical attitudes required for flight on one engine was determined for the model airplane.

The effects of the application of power upon the stability, controllability, lift, and drag of the model airplane were measured. A dynamic-pressure survey of the propeller slipstream was made in the neighborhood of the tail surfaces at three angles of attack.

The added parasite drag of the model airplane resulting from the unfavorable conditions of flight on one engine was estimated to be approximately as follows:

At ceiling, 30 percent.

Full-throttle climb at sea level, 40 percent.

High speed, 19 percent.

From 35 to 50 percent of this added drag was due to the drag of the dead-engine propeller and the other 50 to 65 percent was due to the unsymmetrical attitude of the airplane. The mode of flight on one engine in which the angle of sideslip was zero was found to require less power

than the mode in which the angle of sideslip was several degrees.

INTRODUCTION

The failure of an engine in flight has always presented a serious situation, especially in the case of airplanes having but one engine; under such conditions immediate descent is necessary, regardless of the terrain below. In the case of multiengine airplanes, this situation may be somewhat relieved, for the gliding angle may be made much smaller or horizontal flight may even be continued with one engine dead.

Although modern multiengine airplanes are designed to fly with one engine dead, occasional crashes caused by engine failure do occur. The obvious necessity of providing enough power in the remaining engines, after one has failed, to continue flight is by no means the only question to be considered. Aside from the mechanical problems of isolating the fuel and oil supply systems so that the failure of one engine will not disturb the proper functioning of the remaining engines, there remains the important aerodynamic problem of control. The disposition of engines in the modern multiengine airplane is usually such as to cause a large unbalance of moments and forces at the time of engine failure when adequate control must be provided to bring the airplane into a state of equilibrium compatible with linear horizontal flight.

A study of this emergency may well be divided into two parts: (1) a consideration of the transition period during which the airplane seeks a new attitude for equilibrium; and (2) a consideration of the conditions of flight after equilibrium has been reached, involving the various modes of flight in which equilibrium is attained, the control-surface deflections necessary to maintain equilibrium at various speeds of flight, and the added drag arising from the unsymmetrical attitude of the airplane in flight and from the drag of the dead-engine propeller.

The present investigation, which was made early in 1936, is only a tentative approach to a study of the factors involved in the critical situation arising after engine failure. It was also an experiment to study laboratory methods and technique of handling powered models.

The results, which are somewhat dissociated and lack much of being complete, should be of some interest to both designers and research engineers.

CONSIDERATIONS OF THE PROBLEM AND DESCRIPTION OF THE TESTS

The present investigation has attempted to provide information on several related problems.

<u>The transition phase</u>.- If the airplane is capable of flying with one engine dead and if it has sufficient altitude to avoid danger due to awkward transitional attitudes, the unfavorable effect of the transition phase may be only a temporary mildly unpleasant sensation. If, however, the airplane is traveling close to the ground and at an air speed close to the stall, the danger from this phase may be quite great. Multiengine airplanes usually have a large moment of inertia about the vertical axis and, when (at cruising speed) a wing engine fails, the airplane continues along a straight course for a considerable length of time without any appreciable deviation. The pilot will usually have sufficient time to effect the necessary control measures if the controls are adequate. At air speeds close to the stall, however, there is a possibility that the rudder will not be sufficiently powerful to maintain equilibrium. A precautionary measure would be to remain on the ground, in take-off, until a speed is reached that is considerably higher than the stalling speed. 1.15 V_{min} ?

Little was done on the transition phase of the subject in the present tests except to determine the effect of the following two measures that have been used in the past to reduce the initial yawing moment after engine failure. The first measure tried was to toe-in the vertical control surfaces (on the twin-rudder tail) so that, after engine failure, the slipstream of the active propeller bearing on the inclined surfaces would produce a corrective yawing moment. The second measure was to toe-out the engine nacelles so that the slipstream of the active engine bearing on the vertical sides of the fuselage and control surfaces would produce a corrective yawing moment. The added drag, in normal flight, caused by the inclination of the control surfaces and the engine nacelles was also measured.

The equilibrium conditions of flight on one engine.- A study of the equilibrium conditions of flight on one engine should be directed toward improving the efficiency of flight with one engine dead so that the airplane can maintain sufficient altitude to clear all obstacles on the path to the nearest airport. It is therefore necessary to know something of the forces acting on the airplane, the attitudes it may assume, and the control deflections required to maintain equilibrium.

A fairly comprehensive analysis of these problems is given in reference 1, in which are described three more or less basic attitudes in which a 2-engine airplane can maintain equilibrium with one engine dead. One of the basic modes involves considerable sideslip and appears less favorable than the others from drag considerations. The other two basic attitudes may be described as follows: If it is assumed, for example, that the left-hand engine of a conventional 2-engine transport airplane has failed, equilibrium may be obtained by: (1) Applying enough right rudder, with zero angle of bank, not only to balance the yawing moment of the active engine but also to cause several degrees yaw (sideslip) to the left; (2) Applying right rudder sufficient to balance the yawing moment. The side forces in this method are balanced by the weight component caused by a small angle of bank rather than by the side wind force on the fuselage in the first method. In this attitude, the airplane has zero angle of yaw. The diagram shown in figure 1 illustrates these two attitudes, one of which is essentially an attitude of yaw and the other, an attitude of bank.

In connection with the equilibrium phase of the problem, the added drag due to the two basic modes of flight with one engine dead was determined. The tests were limited to one model airplane, which was considered fairly representative of the conventional 2-engine low-wing transport airplane. Information was also obtained concerning the angles, moments, and forces for equilibrium for this particular model.

Slipstream survey and incidental power effects.- In addition to the parts of the test program described in the preceding paragraphs, certain effects of power on the stability and controllability of the model airplane were investigated. A slipstream-velocity survey was made at the rear end of the fuselage to help determine a suitable location for the tail surfaces.

APPARATUS

Model airplane.- All the tests in the present study were made of a 2-engine low-wing airplane model, which had been constructed for use in a previous research program. The model, although not a direct copy of any airplane, was roughly representative of a conventional type of transport airplane in use in 1934. Its general outlines and structural characteristics are shown in figure 2. Two sets of detachable tail surfaces representing the single- and twin-rudder types were available. Their sizes and angular settings were not quite the optimum for the model airplane, but this fact should not greatly affect the comparisons made in this report. Time did not permit experimenting with sizes and positions other than the ones provided by these two available tail surfaces. The model had no ailerons, flaps, or landing gear.

The two 2-blade propellers were turned by two 5-horsepower electric motors enclosed in N.A.C.A. type nacelles located in the leading edge of the wing. Perforated disks were used to simulate the drag of the engine cylinders, and the nacelles were mounted so that they could be moved spanwise and swiveled laterally about vertical supporting pins.

Model mounting.- The tests were made in the N.A.C.A. 20-foot wind tunnel described in reference 2. A photograph of the test set-up is shown in figure 3. The model was mounted on a ball-bearing universal joint attached to the top of a freely rotating vertical shaft also mounted on ball bearings; this arrangement gave the model freedom in pitch, yaw, and roll. The movements of the model were restrained by fine steel wires attached to the upper surfaces of the wings and the rear part of the fuselage and connected to balances upon which the pitching, the yawing, and the rolling moments were measured. Lift, drag, and lateral force were measured with the regular wind-tunnel balances. The parts of the mounting causing tare drag and tare moments were the fine round piano wires and the short piece of streamline strut directly beneath the model, as shown in the photograph. Provisions were made for changing the angles of yaw and pitch during a test and for keeping the moment wires perpendicular to the wind axis at the same time to prevent mixing the force components. All forces and moments, except the rolling moments, were measured relative to the wind axes. The rolling moments were measured relative to the X body axis.

Instruments for measuring the propeller revolution speed and the power supplied to the motors were located on the test-chamber floor.

SYMBOLS

A list of the symbols used in this report follows:

$C_L = L/qS$, lift coefficient.

L, lift, lb.

S, wing area, sq. ft.

$q = \frac{1}{2} \rho V^2$, dynamic pressure, lb. per sq. ft.

q_s, dynamic pressure in the slipstream.

ρ, air density, slugs per cu. ft.

$C_R = R/qS$, resultant-force coefficient (along wind axis).

R, resultant force along wind axis, lb. (Drag is positive.)

$C_{D_e} = C_R + \frac{2\pi Q \eta_o}{qSJD}$, effective drag coefficient.

Q, sum of the torque of all engines operating, ft.-lb.

η_o, propulsive efficiency taken from propeller tests made at zero angle of attack.

$J = V/nD$.

V, air speed, f.p.s.

n, propeller revolution speed, r.p.s.

D, propeller diameter, ft.

$C_m = M/qSc$, pitching-moment coefficient.

M, pitching moment, ft.-lb.

c, mean aerodynamic chord, ft. (2.54 ft. on model airplane).

$C_n = N/qSb$, yawing-moment coefficient.

N, yawing moment, ft.-lb.

b, wing span, ft.

$C_Y = Y/qS$, lateral-force coefficient.

Y, lateral force, lb.

γ, flight-path angle, deg.

ψ, angle of yaw, deg.

β, angle of sideslip, deg.

Φ, angle of bank, deg.

α, angle of attack, deg.

δ_r, angle of rudder.

δ_e, angle of elevator.

e, a factor by which C_{D_i} is divided to make

$$C_D - C_{D_i} = \text{constant}$$

$C_D = C_{D_c}$, total drag coefficient.

$C_{D_i} = D_i/qS$, induced drag coefficient.

f = parasite drag/q, equivalent parasite area of airplane in normal 2-engine flight, sq. ft.

Δf_p, equivalent parasite area of dead propeller, sq. ft.

Δf_a, equivalent parasite area corresponding to the increase in the drag of the airplane, other than Δf_p, caused by flight with a dead engine, sq. ft.

METHODS

Since the power effect of the model engines will vary with blade angle V/nD, and propeller revolution speed, it is advantageous to decide at the beginning of the investigation on the design characteristics of the airplane that the model represents and from then on to express all results in terms of this airplane. It is convenient, and in the present case not seriously detrimental, to neglect scale effect. An arbitrary tare drag, which approximated the actual tare drag, was deducted from the total drag in order to bring the final drag coefficient to a desired value.

The following characteristics were chosen for the airplane that the model was to represent:

Scale of model - - - -	5:1
Wing span - - - - - - - -	75.5 ft.
Wing area - - - - - - -	850 sq. ft.
Gross weight - - - - - -	13,600 lb.
Wing loading - - - - -	16 lb. per sq. ft.
Aspect ratio - - - - - -	6.72
High speed - - - - - -	about 185 m.p.h. (sea level).
Power - - - - - - - - - -	2 engines rated 700 horsepower at 1,800 r.p.m.
Propellers - - - - - - -	controllable (two settings) diameter 10 ft.; 2 blades; low blade angle, 22°; high blade angle, 25°.

Equilibrium Conditions of Flight on One Engine

In the present investigation the equilibrium conditions of flight on one engine were obtained by measuring the forces and moments on the model at several angles of attack and of sideslip with various rudder settings and then cross-plotting the results. As the determination of the conditions of complete equilibrium by means of this method requires an excessive number of cross plots, the pitching and rolling moments, which were small enough to have an inappreciable effect on the equilibrium attitude, were measured but were not brought to zero. The only correction made to compensate for the rolling and pitching moments was the addition of increments of drag, which were calculated to be equivalent to the drag produced by the deflections of the control surfaces necessary to bring the pitching and the rolling moments to zero. These increments were very small.

All the tests were made with the right propeller operating and the left propeller locked vertically, because only with the dead-engine propeller locked could representative conditions be obtained. Sufficient data on the drag of locked and freewheeling propellers are available (references 3, 4, and 5) to make the necessary corrections for the propeller-operating condition. Both propellers were set at 22° at 0.75 R in all the tests reported herein.

The data for calculating the drag characteristics in the banked mode of flight (zero yaw) were obtained from the tests covering the attitude of yaw, as the angle of zero sideslip (yaw) was in the range of sideslip angles tested. The small angle of bank of the airplane in this mode of flight (about 2°) should cause no additional drag.

Slipstream Survey and Power Relations and Effects

Survey of slipstream.- A pressure survey of the slipstream was made to determine its velocity and its position relative to the tail surfaces. In order to obtain the survey, the tail surfaces were removed and a vertical bank of static- and total-head tubes was mounted in the general location of the tail surfaces. A photograph of the survey apparatus in place is shown in figure 4. The horizontal bar that supported the bank of pressure tubes was made so that it could be moved spanwise, thus covering the entire slipstream. The pressures were recorded photographically by a multiple manometer. Surveys were made at three values of V/nD for each of three angles of attack and, during the survey behind each propeller, the other was locked vertically to represent conditions of flight with one engine dead.

Power relations.- From propeller tests and drag tests of the model, data were available for calculating the curves of thrust horsepower available and required for the simulated airplane. The same data were used to construct a curve of V/nD against C_L, representing full-throttle conditions, which was found useful in determining the full-power conditions of the tests. The only other power condition investigated in these tests was that of level flight. The coefficients representing level flight were obtained from plots of the coefficients at points where C_R was zero.

<u>Coefficient C_{D_e}</u>.- The general method used closely followed that given in reference 6. Considerable variation in certain places was necessary, however, to make allowance for the different conditions in the present tests. The effective drag coefficient C_{D_e}, developed in reference 6 was used. The effective drag when the propellers are operating is merely the calculated propeller thrust (from propeller curves) plus the drag-balance reading. Inasmuch as the propeller efficiency used in calculating C_{D_e} is based on propeller data taken at zero angle of attack, the C_{D_e} at higher angles of attack includes an increment equivalent to the loss of efficiency caused by inclining the thrust axis. The effect of thrust-axis inclination can thus be conveniently included, as practically all propeller tests upon which performance calculations are based are made with the thrust axis parallel to the wind axis.

<u>Power-on polars</u>.- The drag coefficient C_{D_e} may be used to derive power-on polars representing various power conditions. A level-flight polar may be made by merely calculating C_L and C_{D_e} at various angles of attack, for conditions where C_R is zero. The test procedure is to take readings of lift, drag, propeller revolution speed, and torque at various throttle settings (values of C_R) for the complete range of angles of attack. These values of C_L and C_{D_e} are then plotted against C_R and (for level flight) values of C_L and C_{D_e} are picked off where $C_R = 0$.

Values of C_R other than zero represent other power conditions in either gliding descent or climb. In reference 6, C_R is conveniently expressed in terms of the tangent of the flight-path angle:

$$C_R = - C_L \tan \gamma$$

A polar may thus be obtained for any angle of climb or descent within the capabilities of the airplane from full power to maximum negative torque. Moment coefficients representing level flight can be obtained in the same manner as are the lift and drag coefficients.

RESULTS AND DISCUSSION

Power Relations and Transition Effects

Power curves.- The curves of thrust horsepower available and required for the simulated airplane are shown in figure 5. The break in the curve of thrust horsepower available is caused by the change in blade-angle setting. If one engine failed, the pilot would probably set the active propeller at low pitch to obtain the maximum power from the operating engine.

As the thrust horsepower can be expressed in terms of V/nD and V for any particular airplane, the curve of thrust horsepower available at full throttle may, by the use of propeller curves, be converted to a curve of V/nD against V and, with a known wing loading, V/nD for full power may be plotted against C_L as in figure 6.

Transition effects, preliminary plots.- An example of the type of preliminary plot used to obtain the curves, which show the effects of toeing-in the fins and rudders of the model equipped with the twin-rudder tail, is given in figure 7. Values of C_L, C_{D_e}, C_R, and C_n are plotted against V/nD in figure 7. The coefficients C_L, C_{D_e}, and C_R represent normal conditions of flight on two engines, whereas the curve of C_n represents the yawing moment that would occur if one of the engines suddenly stopped. The values given by the coefficient curves at their intersections with the vertical line passing through $C_R = 0$ represent level-flight conditions; full-power conditions are represented by the intersection of the coefficient curves with the other vertical line, which is located by the intersection of the C_L curve with the curve from figure 6 of C_L against V/nD for full power. The coefficients lying between the two vertical lines represent all the possible climbing conditions for the specified angle of attack.

Effect of toeing-in vertical tail surfaces.- The coefficient values representing full-power conditions from figure 7, and from other similar plots, were corrected for jet-boundary conditions and plotted in figures 8 and 9. The upper curves in both figures show the increase in drag coefficient, in normal 2-engine flight, of toeing-in the fins and rudders as illustrated by the sketch of the tail in figure 8. The curves in the lower half of each figure show the reduction in initial yawing moment, after the failure of one engine, resulting from this measure.

It will be noticed in figures 8 and 9 that the corrective effect of toeing-in the fins and rudders is greater if the right engine fails than if the left engine fails. This effect may be explained by the fact that only the upper half of the slipstream impinges on the rudder and the twist of the slipstream from the right-hand engine is such as to wash out the effective toe-in angle; whereas the opposite is true of the slipstream of the left-hand engine. In both cases, however, the corrective effect of toeing-in the vertical tail surfaces is fairly small.

Effect of toeing-out engines.- Another possible method of reducing the initial yawing moment at the instant of engine failure is by toeing-out the engines so that the slipstream bears on some vertical surface, such as the fuselage or the rudder. This method will naturally be more effective for high-wing than for low-wing airplanes because, in the case of the high-wing type, the slipstream will be more likely to strike the fin and rudder.

The curves in figure 10, which were obtained by the same general method as those in figures 8 and 9, show the effect of toeing-out the engines 5° and 10°. The centers of the propeller hubs were the same distance apart at both angles. With the engines set at 5°, the initial yawing moment (at $C_L = 1.0$) is reduced 15 percent and, at an angle of 10°, it is reduced 20 percent. The added drag due to the angular setting of the engine (which includes an increment equal to the loss in propeller efficiency due to the angle of yaw) is considerable.

A brief examination of the results shown in figures 8, 9, and 10 indicates that an attempt to reduce the yawing moment after engine failure by either of these methods would be quite impractical. The designer would undoubtedly feel that the beneficial effect of these measures would cost too much in terms of drag. It appears wiser merely to increase the size of the rudder to insure yawing control in case of engine failure at low air speeds.

Equilibrium Conditions of Flight on One Engine

Preliminary charts.- Figures 11 to 19 deal entirely with the study of the equilibrium conditions of flight after one engine has failed. The dead-engine propeller was locked with the propeller vertical in all cases. A considerable number of plots and cross plots of data were necessary to obtain the final data representing equilibrium conditions. A few of the final plots showing interesting and useful relations between the various factors involved are given in this report. These figures relate largely to the yawed condition of flight on one engine, as previously described; in all cases the left-hand engine was stopped. The figures represent level-flight conditions at sea level.

Figures 11, 12, and 13 show the variation of yawing-moment coefficient and lateral-force coefficient with sideslip angle for various rudder angles and angles of attack. The rudder angles and yaw angles giving zero yawing moment and zero lateral force are shown as figures 11(c), 12(c), and 13(c). The intersection of the curves of C_Y and C_n determines the sideslip and rudder angles for equilibrium for each particular angle of attack. It appears from the figures that the twin rudders would be insufficient to maintain equilibrium at angles of attack higher than 13°.

Figure 14 shows the variation of pitching-moment coefficient with sideslip angle for the three angles of attack tested. Rolling moments were also measured but they were so erratic as to be useless for showing trends; however, average values did show the rolling moment to be small in all cases. The dihedral angle of the model airplane was somewhat less than that commonly found in current design and, for this reason, its measured rolling moment when sideslipped is believed to be less than normal. The pitching moments in figure 14 seem to be quite erratic but they indicate, in general, a reduction of pitching moment with sideslip angles above 2-1/2° and a considerable increase in pitching moment with rudder angle.

Figures 15(a) and 15(b) show the variation of lift coefficient and effective drag coefficient with sideslip angle for various rudder angles, the short vertical lines representing equilibrium sideslip angles. Figures 15(c) and 15(d) are cross plots taken from 15(a) and 15(b) at the equilibrium sideslip angles. The coefficient values at the intersections of the vertical lines in figures 15(c) and 15(d) represent equilibrium conditions of force along the X, Y, and Z axes and of yawing moment. The rolling and pitching moments are not quite in balance, but calculated corrections were made before the equilibrium coefficients were plotted in polar form.

Final polars and power curves.- The polars for the single-engine and for the 2-engine level-flight condition are shown in figure 16. The polar for the banked mode of flight on one engine was obtained from the previous curves, figures 11, 12, 13, and 15, at the angle of zero sideslip. The lateral force due to the deflected rudder was in this case assumed to be balanced by the gravity force caused by a small angle of bank (about 2°). The angle of bank does not affect the drag. Figure 16 shows the banked mode of flight to be somewhat better than the yawed mode. The disadvantage of the yawed mode results from the added airplane drag and the loss in rudder effectiveness caused by the angle of yaw or sideslip. The yaw angle also results in a small loss of propeller efficiency.

Drag analysis.- At a lift coefficient of 0.725, corresponding to a climbing air speed of 93 miles per hour, the additional drag caused by the unfavorable conditions of flight on one engine is about 15 percent of the normal drag. A comparison of figure 16 with figure 17, which shows polars for various propeller operating conditions, indicates that about four-tenths (6 percent) of the increase in drag is caused by the dead propeller and about six-tenths (9 percent) by the rest of the airplane. The dead propeller has a particularly bad effect, for not only does it contribute a drag of its own but it also results in a moment equal to twice its drag multiplied by the distance of the propeller hub from the axis of symmetry. This condition is caused by the fact that the active propeller must supply additional thrust to overcome the drag of the dead propeller. Obviously, controllable propellers that could be feathered to 90° would be a great help in emergencies of this kind.

The polars given in figure 16 were converted to thrust horsepower required (t.hp.$_r$) for the airplane represented by the model and are plotted against air speed in figure 18. The thrust horsepower available (t.hp.$_a$) curve from figure 5 is also included. The thrust horsepower available for flight on one engine is, of course, half of that for normal 2-engine flight.

As previously mentioned, the added drag resulting from the conditions of flight on one engine is 15 percent, which is largely the result of an increase in parasite drag. As the parasite drag at climbing speed is approximately half of the total drag, assuming $e = 0.8$, the increase in equivalent parasite area $\Delta f/f$, will be about 30 percent. This value approximates the drag existing at ceiling on one engine, though it is probably a little optimistic. In full-throttle climb at sea level, the value of $\Delta f/f$ will be considerably greater than at ceiling.

The rate of climb at sea level cannot be found by the usual method of dividing the excess power (above that required for level flight) by the airplane weight because, as the pilot opens the throttle to make the climb, the power required to overcome the drag of the airplane increases, owing to the larger rudder angle required, and the excess power available for climb therefore becomes less than indicated.

With the data available in the present case, however, it is possible to estimate the added drag in climbing flight and the initial rate of climb. At 93 miles per hour, the value of $\Delta f/f$ was found to be 30 percent. The ratio $\Delta f/f$ may be broken up into two parts: $\Delta f_p/f$ and $\Delta f_a/f$, where Δf_p is the equivalent parasite area of the dead propeller and Δf_a is a parasite area equivalent to the increase in drag of the airplane, exclusive of Δf_p, caused by the conditions of flight on one engine.

It may be assumed with reasonable accuracy that for flight with one (of two) engines dead,

$$\frac{(\Delta f_a)_a}{(\Delta f_a)_b} = k\,\frac{(t.hp.)_a}{(t.hp.)_b}$$

where subscripts a and b represent conditions resulting from different throttle openings of the active engine for a given air speed and where the proportionality factor k is a constant with a value equal to or slightly greater than 1.

The calculations for the present airplane are as follows:

As before mentioned; $\Delta f_p = 0.4\ \Delta f$ and $\Delta f_a = 0.6\ \Delta f$; therefore $\Delta f_p = 0.4 \times 0.30\ f = 0.12\ f$, and $\Delta f_a = 0.6 \times 0.30\ f = 0.18\ f$.

For level flight at 93 m.p.h., $t.hp._a/t.hp._r = 480/340$; therefore $(\Delta f_a)_{climb} = \Delta f_a \times k \times (480/340)$.

If k is assumed to be equal to 1.1, $(\Delta f_a)_{climb} = 0.18\ f \times 1.1\ (480/340) = 0.28\ f$. The total increase of equivalent parasite area in full-throttle climb at sea level will be $\Delta f_p + (\Delta f_a)_{climb} = 0.12\ f + 0.28\ f = 0.40\ f$.

In normal 2-engine flight the thrust horsepower required for level flight at 93 miles per hour is 294. About half the power (147 t.hp.) is used to overcome parasite drag and the other half to overcome induced drag. The thrust horsepower required to overcome the parasite drag of the airplane climbing on one engine at sea level will be

$$147 \times 1.40 = 206 \text{ t.hp.}$$

The total power required will be

$$206 + 147 = 353 \text{ t.hp.}$$

The excess power left for climbing will be

$$480 - 353 = 127 \text{ t.hp.}$$

and, as the airplane weighs 13,600 pounds, fully loaded, its initial rate of climb with that load will be

$$(127 \times 33{,}000)/13{,}600 = 308 \text{ ft. per min.}$$

The value of $(f + \Delta f)/f$ for high speed at sea level will be approximately equal to the ratio $(t.hp.)_1/(t.hp.)_2$

where $(t.hp.)_1$ is the thrust horsepower required at high speed on one engine and $(t.hp.)_2$ is the thrust horsepower required in normal 2-engine flight at the same air speed. For the present airplane,

$$(f + \Delta f)/f = 590/496 = 1.19$$

which gives a value of 0.19 for $\Delta f/f$ at high speed on one engine.

In a summarization of the case for the present airplane, the approximated values of $\Delta f/f$, which represent an average for the yawed and banked modes of flight on one engine, are as follows:

At ceiling, 0.30.

Full-throttle climb at sea level, 0.40.

High speed, 0.19.

Application.- It should be pointed out that these values of $\Delta f/f$ are the result of some fairly loose approximations and that they apply strictly only to the airplane represented by the model. There are a great many variables in the design of airplanes that will have a marked influence on the ratio $\Delta f/f$. Among these variables are: propeller diameter, number of blades, blade angle, engine spacing, and rudder design. The values of $\Delta f/f$ will also vary directly with the ratio of engine power to f. Also, most modern 2-engine transport airplanes use 3-blade propellers instead of 2-blade ones, such as used in the present tests. For this reason alone, the values of $\Delta f/f$ for modern airplanes may possibly be 25 percent greater than the values given for the present airplane model. It is beyond the scope of this report to give consideration to the quantitative effects of all the factors that affect the flight of airplanes with dead engines. The best source of information on this subject at the present time is found in reference 1, which should be consulted in all performance calculations of this type.

Equilibrium attitudes.- Some of the equilibrium attitudes and control angles necessary for flight on one engine can be examined by the aid of figure 19. In this figure are shown the equilibrium angles of sideslip and bank and the equilibrium rudder angles for the two basic modes of flight on one engine. In the banked mode of flight, the sideslip angle is zero and the angle of bank is about 2°, increasing slightly with increase in air speed. The rudder angle increases with a decrease in air speed but is much lower than the angle necessary for the yawed mode of flight. In the yawed mode of flight, the rudder is inadequate to maintain equilibrium below an air speed of about 72 miles per hour. In this mode of flight, the angle of bank is zero and the angle of sideslip is under 10°, decreasing rather rapidly with increasing air speed.

The fact that the rudder angle for the banked mode of flight is considerably less than for the yawed mode of flight is very important, because there is always a strong possibility that the rudder will be inadequate and any means of increasing its effectiveness will be of value. For this reason, as well as for the purpose of securing a lower drag, the banked mode of flight is much superior to the yawed mode.

<u>Design factors</u>.- In dealing with the emergency situation arising on the failure of one engine of a twin-engine or a multiengine airplane, the designer should pay particular attention to the rudder design in addition, of course, to the obvious necessity of maintaining the maximum excess of power available, with one engine dead, over that required for level flight. The rudder (and fin) should be somewhat larger than the size required for ordinary flight purposes and it should have as great an aspect ratio as is structurally feasible for the purpose of maintaining high values of L/D, for the vertical tail surfaces, at large rudder angles.

The full-feathering controllable propeller that can be set to 90° after engine failure is an important asset in flight with one engine dead. It is of especial value in installations where the normal blade angle is low, for the drag of a dead propeller increases rapidly with decrease in blade angle. A full-feathering propeller will not only reduce the drag of the dead propeller to a large degree but it will also relieve the load, as well as the drag, on the already heavily loaded rudder.

Slipstream Survey and Incidental Power Effects

<u>Slipstream survey</u>.- The results of the slipstream sur-

vey are shown in figure 20 as contours of q_s/q, the ratio of the dynamic pressure in the slipstream to the dynamic pressure in the undisturbed air stream. The values of V/nD for the surveys shown in figure 20 represent a flight condition about midway between level flight and full-power climb. Surveys made at two other values of V/nD are not shown here. The survey behind each propeller was made with the other propeller locked. The propeller disks are shown in the figure and the positions of the tail surfaces have been drawn in their proper location. The view shown is looking forward and parallel to the propeller axis. It will be noted that the slipstream pattern has been greatly distorted in passing over the wing and that, as the angle of attack is increased, the entire slipstream is deflected upward by the free air stream. These contours may be of help to designers in locating tail surfaces.

Effect on airplane polar of propeller operating condition.- The drag of the dead-engine propeller will have a considerable influence on the performance of an airplane after engine failure. References 3, 4, and 5 provide data for computing this effect, but it has been considered desirable to include in this study tests to show the effect of the propeller operating condition on the lift-drag polar of the model airplane. The results of the tests for that purpose are shown in figure 17. It should be noted that the power-on polar for level flight is the same as the polar with propellers removed in all but the high-lift range. This result means that level-flight characteristics, except at low speeds, can be calculated from the usual polar obtained with power off (no propellers). In reference 6 it is shown, however, that the power-off polar cannot be used to calculate full-power climbing characteristics unless a suitable value of the factor e is used.

It is observed that a propeller locked at 22° adds considerably to the drag of the airplane and the drag with the propeller idling (turning over the electric motor against friction torque) is somewhat less. The effect of locked or idling propellers on the maximum lift coefficient is small, though the power-on condition for level flight seems to prevent the early stall and increases the maximum lift by about 21 percent.

Effect of power on stability and controllability.- Figure 21 is a comparison of the pitching moments of the model airplane with power on and with power off (propellers removed). As was previously mentioned, time did not permit experimenting with different tail areas and settings and it was not known at the time the tests were made whether or not the tail areas or settings were correct. The trim angle and stability were not satisfactory; the destabilizing effect of adding power, however, is clearly shown.

Figure 22 gives an interesting comparison of the pitching moments with the twin- and single-rudder tails with which the airplane model was alternately equipped. Although the horizontal surfaces of the twin-rudder tail were of somewhat smaller area than those of the single-rudder tail, the twin-rudder tail is observed to be more effective. This quality of the twin-rudder tail has been known for some time and is usually attributed to the end-plate effect of the twin rudders, which tend to prevent tip loss. All the moments in this report are given with respect to the pivot point, which was at 32 percent of the mean aerodynamic chord (see fig. 2) except in the case of figures 21 and 22 where the moments were transferred to a point 5 percent of the mean aerodynamic chord ahead and 12 percent of the mean aerodynamic chord above the pivot point. The point about which the pitching moments in figures 21 and 22 are given is at 27 percent of the mean aerodynamic chord.

Figure 23 shows that the addition of power increases the effectiveness of the elevator control. Although the curves appear to be somewhat erratic, the effect of power is clearly shown. The curves in figure 24 for level-flight power conditions show the increase in drag due to elevator deflection.

The yawing moments plotted against yaw angle for the model airplane equipped with the single- and the twin-rudder tails are given in figure 25, which shows the twin-rudder tail to be less effective than the single-rudder tail in regard to yawing moments, though both have the same vertical tail area. Figures 26 and 27 show the rudder effectiveness, on this type of airplane, to be very little altered by the application of power.

CONCLUSIONS

The following conclusions refer, in general, to 2-engine airplanes similar to the model tested.

1. Toeing-out the engines or toeing-in the twin rudders and fins were impractical methods of reducing the yawing moment after engine failure on the low-wing 2-engine airplane that the model represented.

2. The use of power in the present tests produced a destabilizing effect on the pitching moment of the airplane model.

3. The yawed mode of flight on one engine after engine failure increased the drag of the airplane somewhat more than the banked mode of flight.

4. The increase in the parasite drag of the airplane in three conditions of flight with one engine dead was approximately as follows: ceiling, 30 percent; full-throttle climb at sea level, 40 percent; high speed, 19 percent.

5. The tests indicate that a powerful and efficient (high L/D) rudder would be necessary for efficient flight with a dead engine.

6. Full-feathering controllable propellers may be important assets in flight with a dead engine, especially where the normal blade-angle settings of the propellers are low.

7. In the yawed mode of flight on one engine, the yaw angle averaged about 5° and the rudder became inadequate at low air speeds.

8. In the banked mode of flight on one engine, the rudder angle required to maintain equilibrium was much less than for the yawed mode and the required angle of bank was only about 2°.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 14, 1938.

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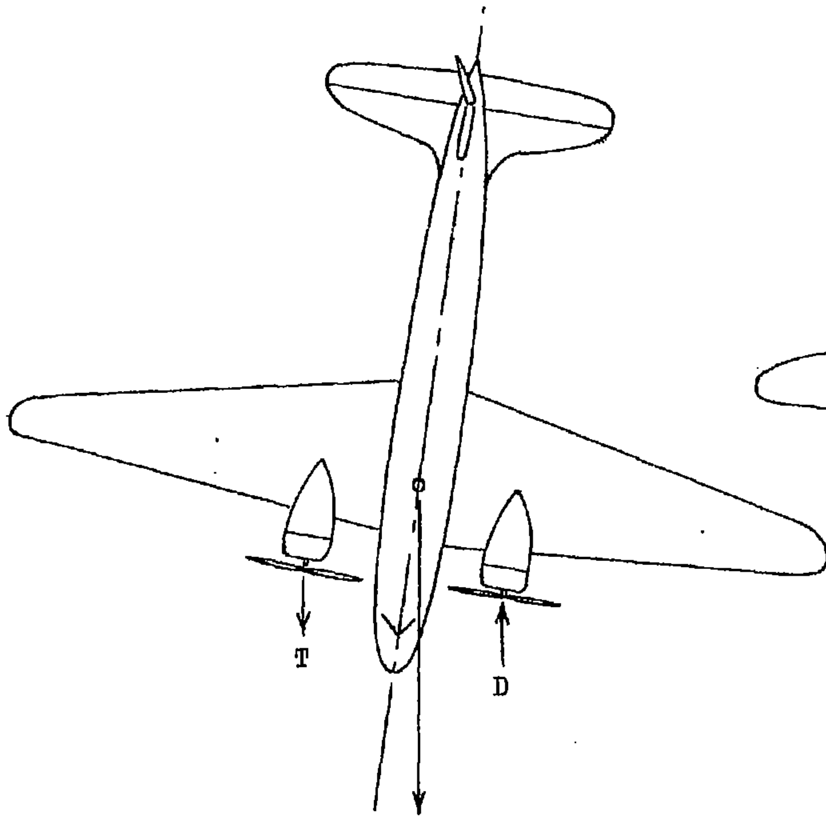
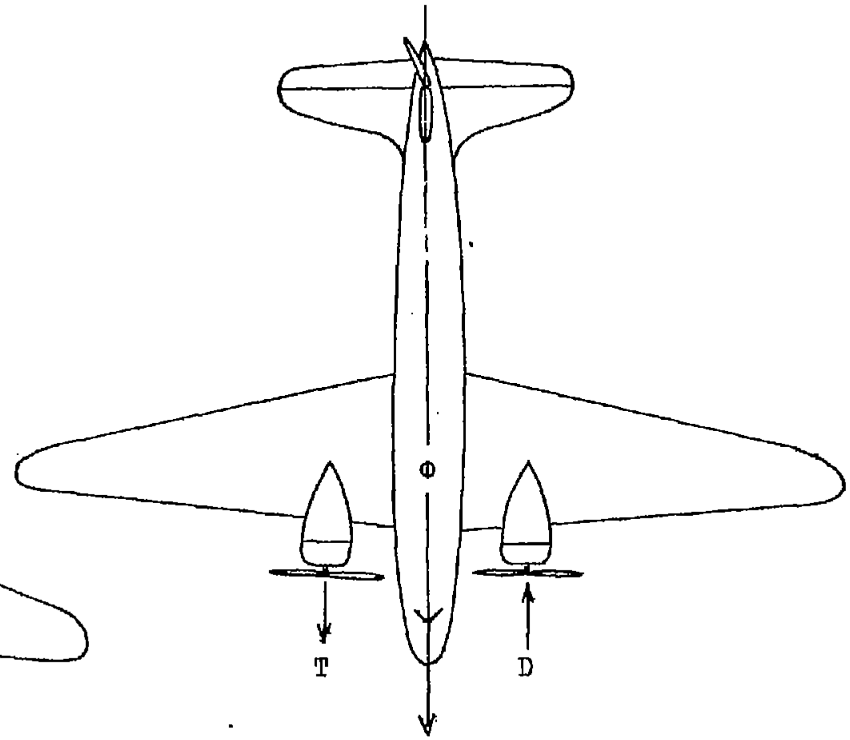
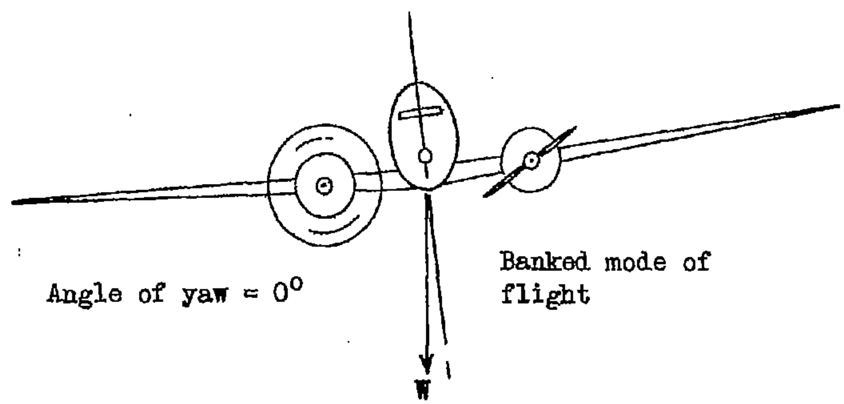


Angle of bank = 0°

Yawed mode of flight





Angle of yaw = 0°

Banked mode of flight

Figure 1.- Two basic modes of flight after engine failure.

Tail Areas

	Single rudder (sq. ft)	Twin rudder (sq. ft.)
Total horizontal surface[1]	7.00	6.45
Elevator "	2.60	——
Total vertical "	2.65	2.65
Effective rudder "	1.65	1.55

[1]Horizontal surface includes area common to fuselage and tail surface.

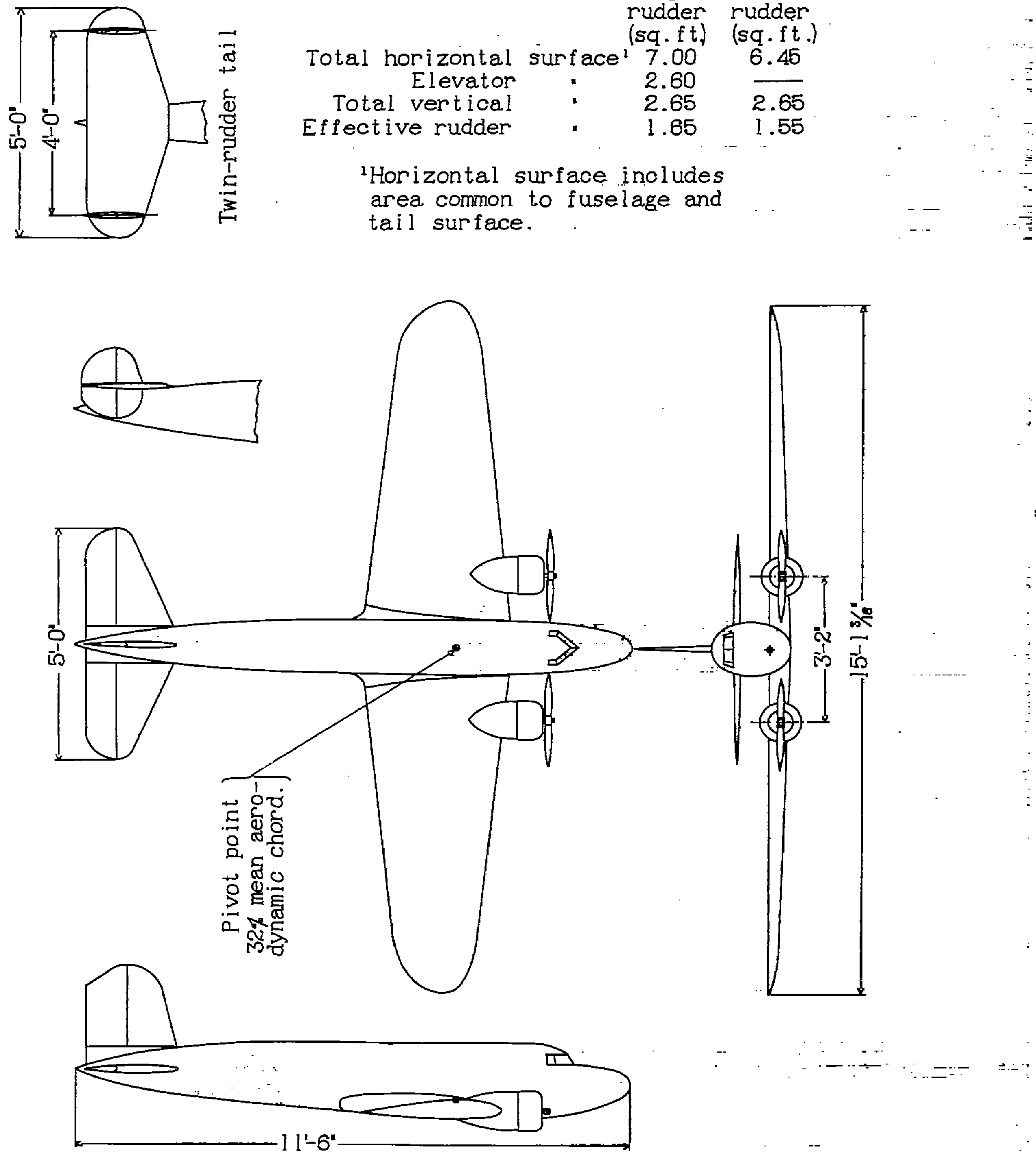


Figure 2.- Three-view sketch of airplane model.

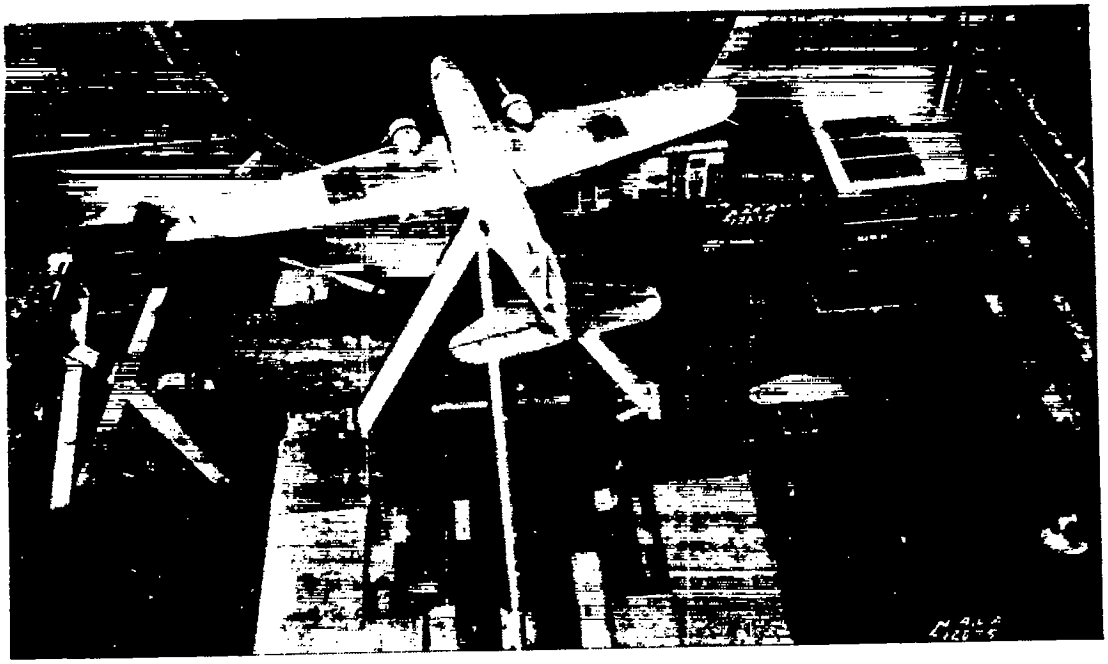


Figure 3. - Model at angle of yaw in wind tunnel.

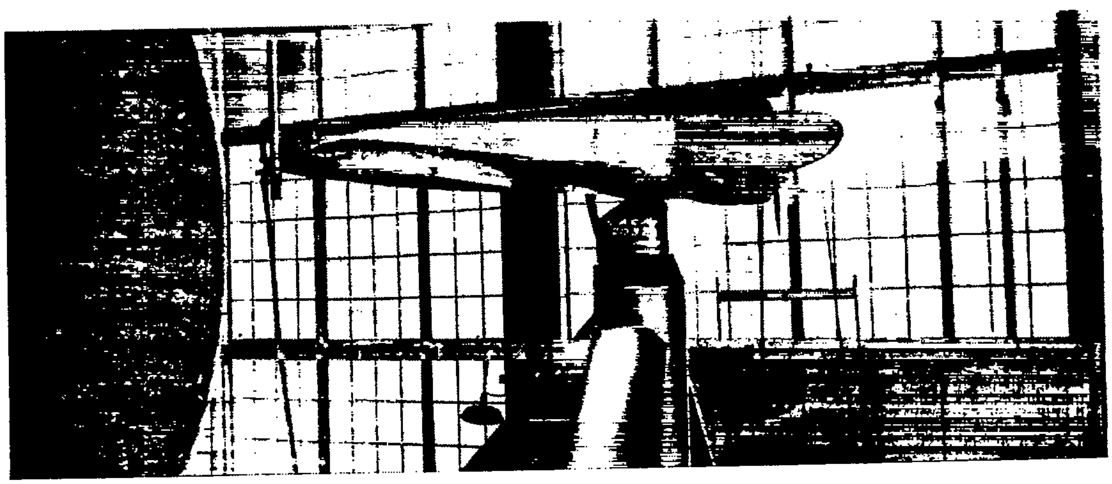


Figure 4. - Set-up for slipstream survey.

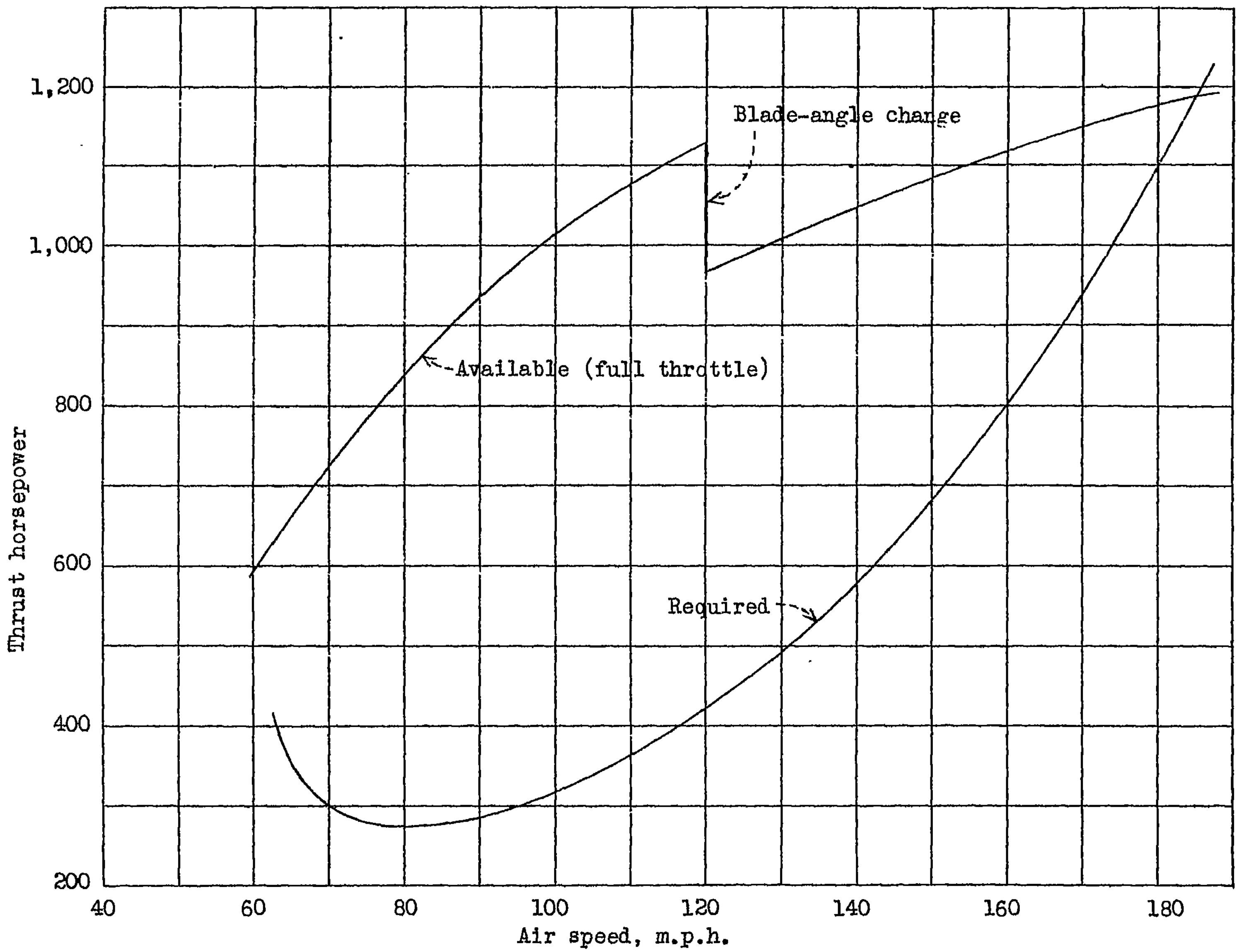


Figure 5.- Power curve for the airplane represented by the model. Level-flight sea-level conditions.

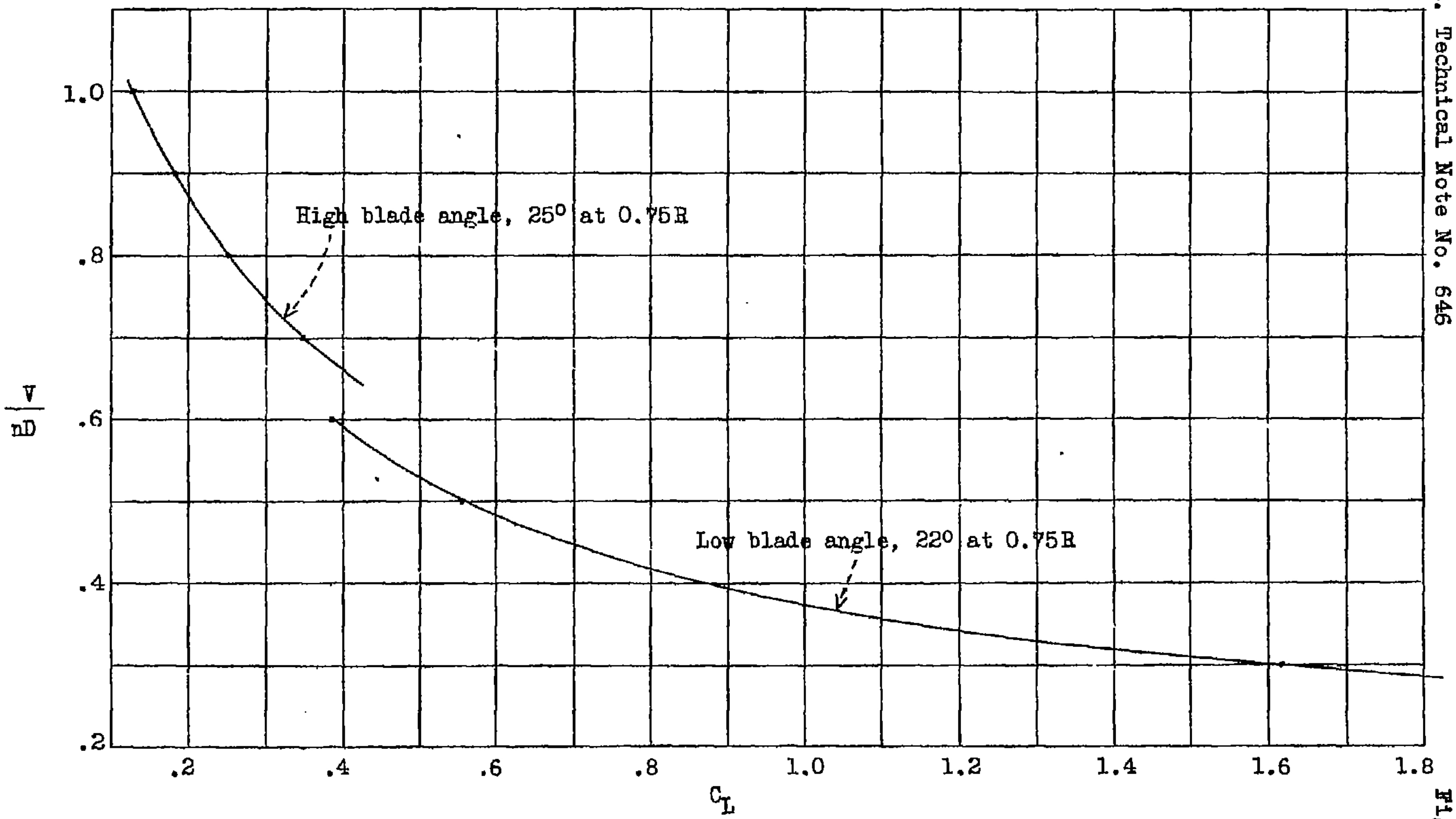


Figure 6.- Variation of V/nD for full power with C_L for the airplane represented by the model.

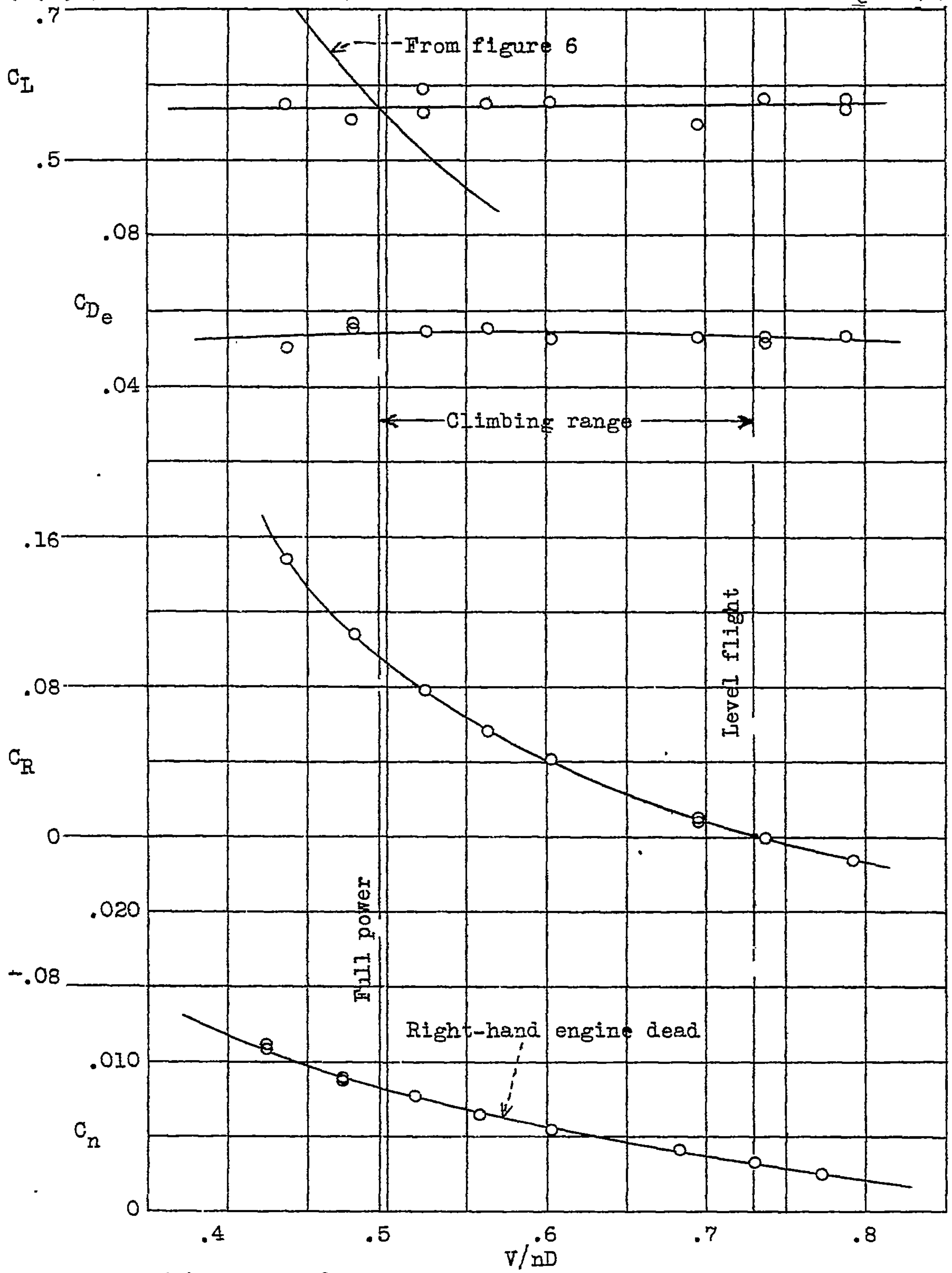


Figure 7(a). $\alpha = 6^\circ$.
Airplane characteristics with power on. Fins and rudders at 0°. Both engines operating except where noted.

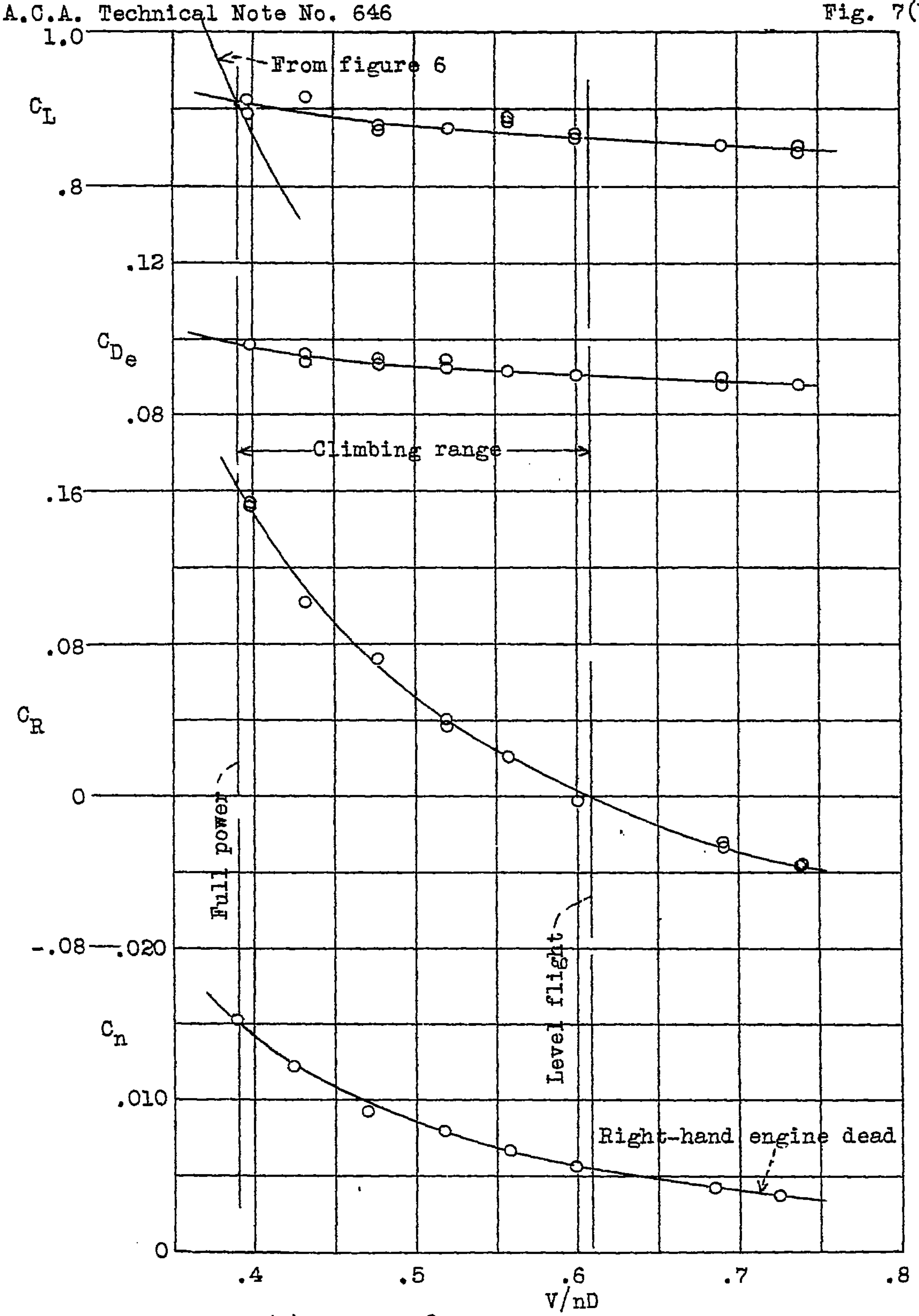


Figure 7(b). α = 10°.

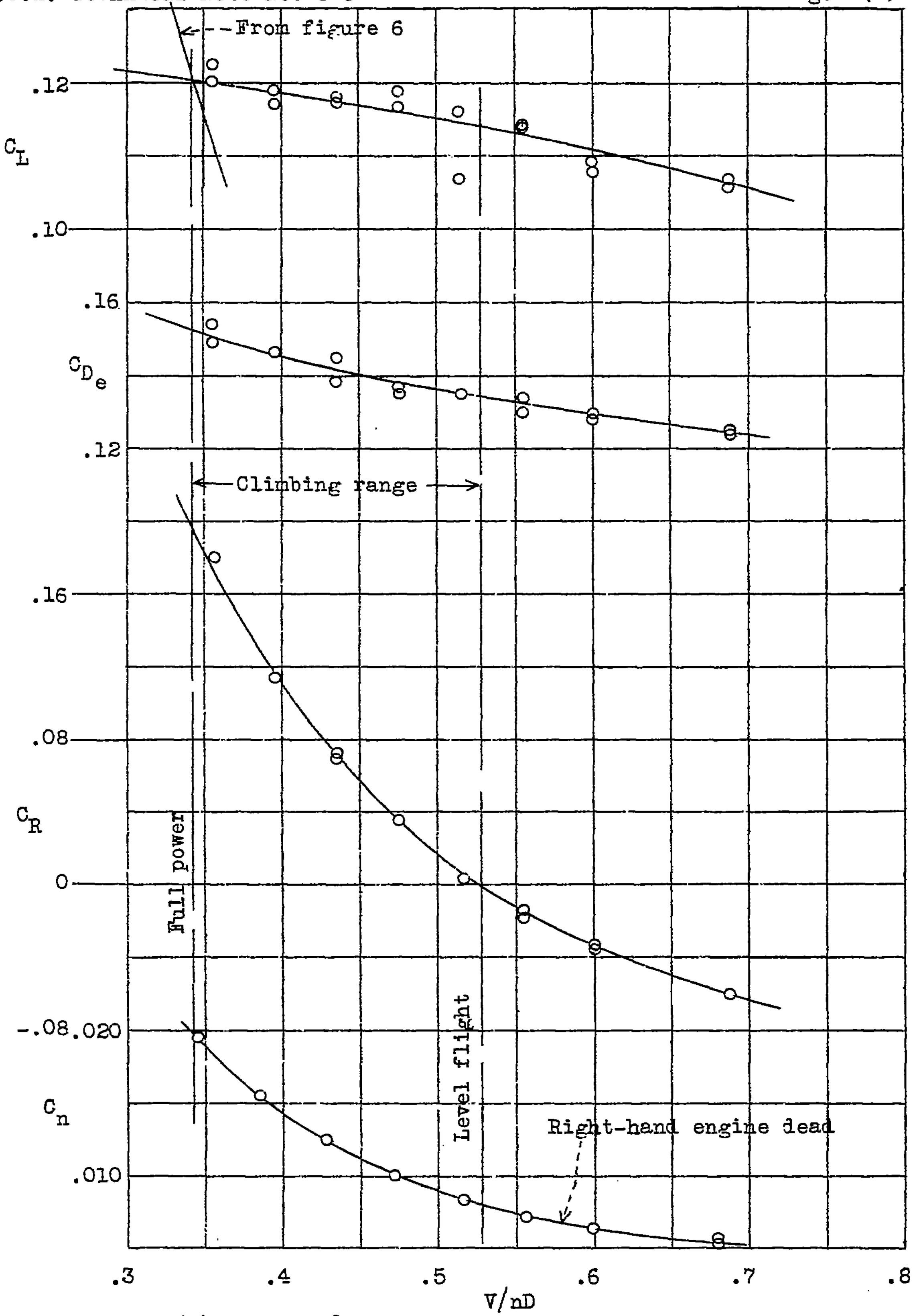


Figure 7(c). α = 13°

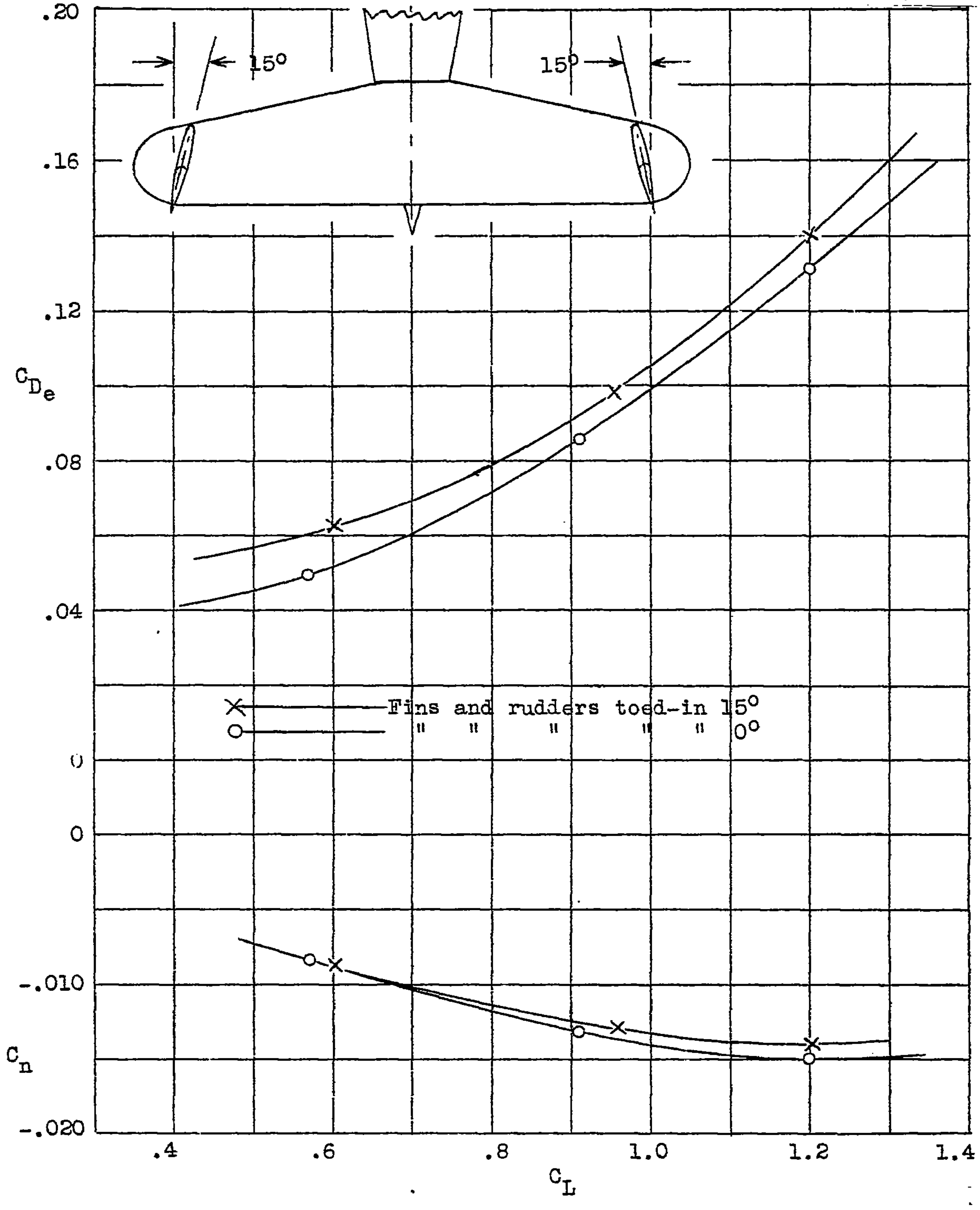


Figure 8.- Effect of toeing-in fins and rudder on airplane drag in normal 2-engine flight and on yawing moments after failure of left-hand engine. Full power on right-hand engine.

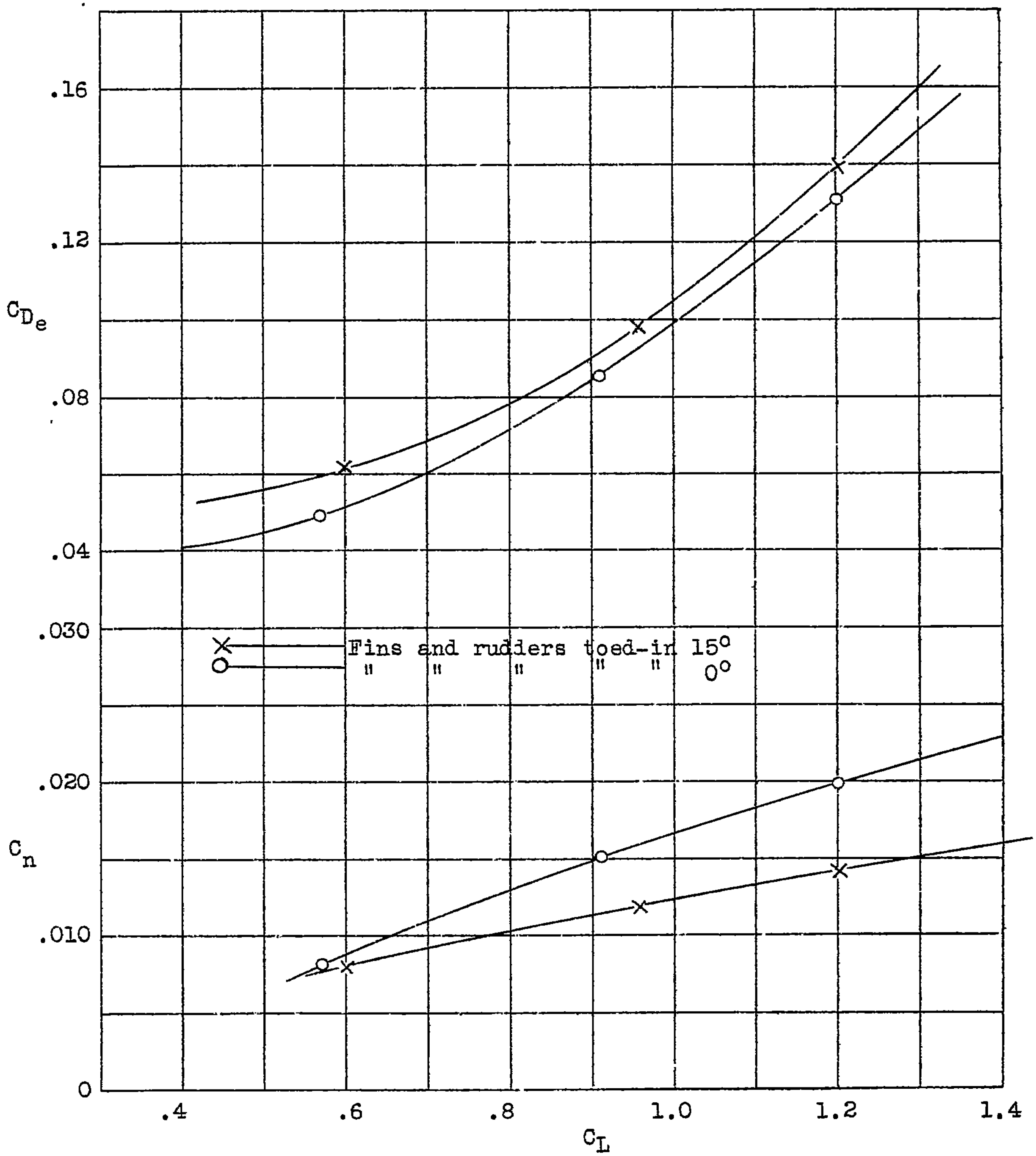


Figure 9.- Effect of toeing-in fins and rudders on airplane drag in normal 2-engine flight and on yawing moments after failure of right-hand engine. Full power on left-hand engine.

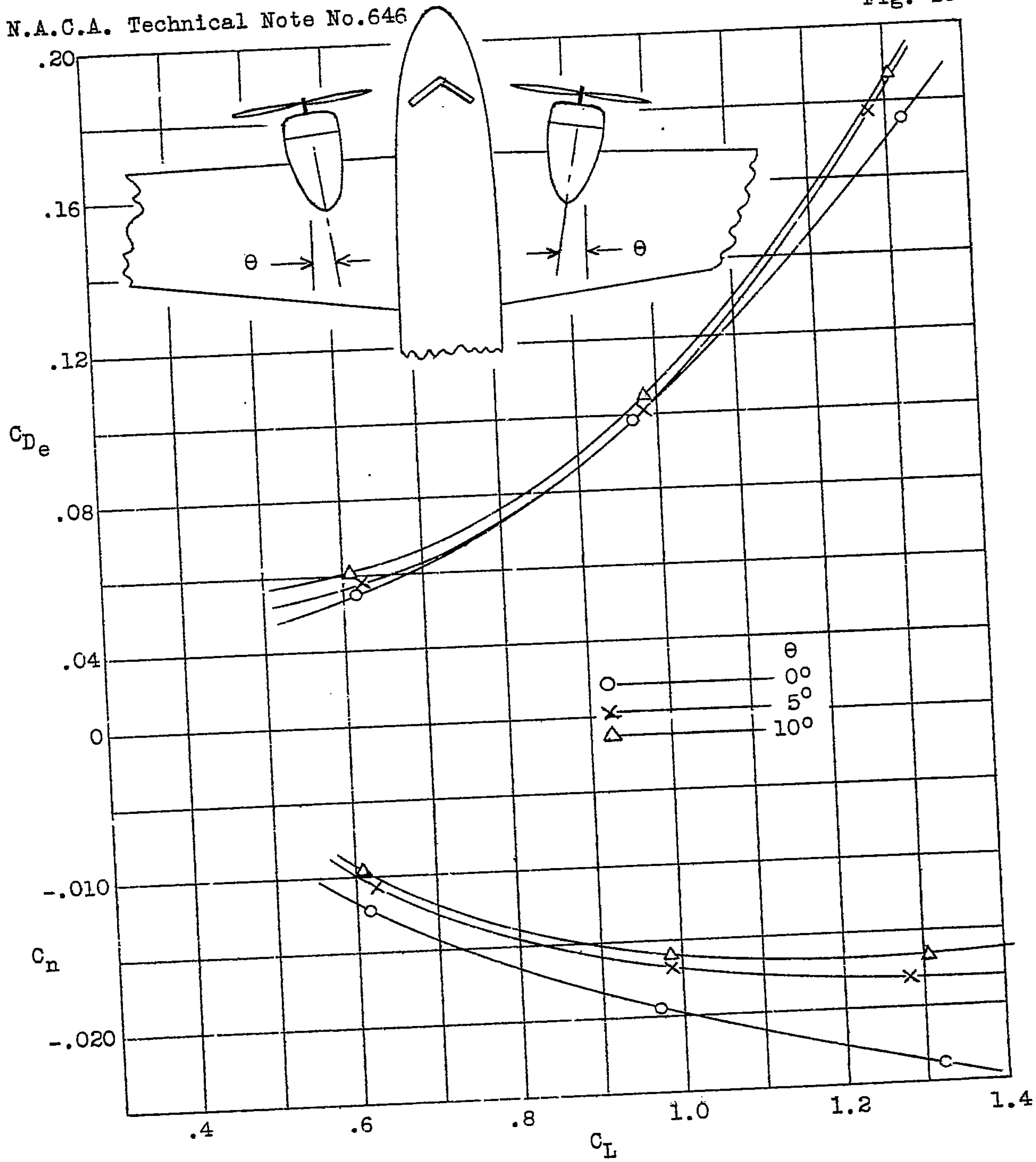
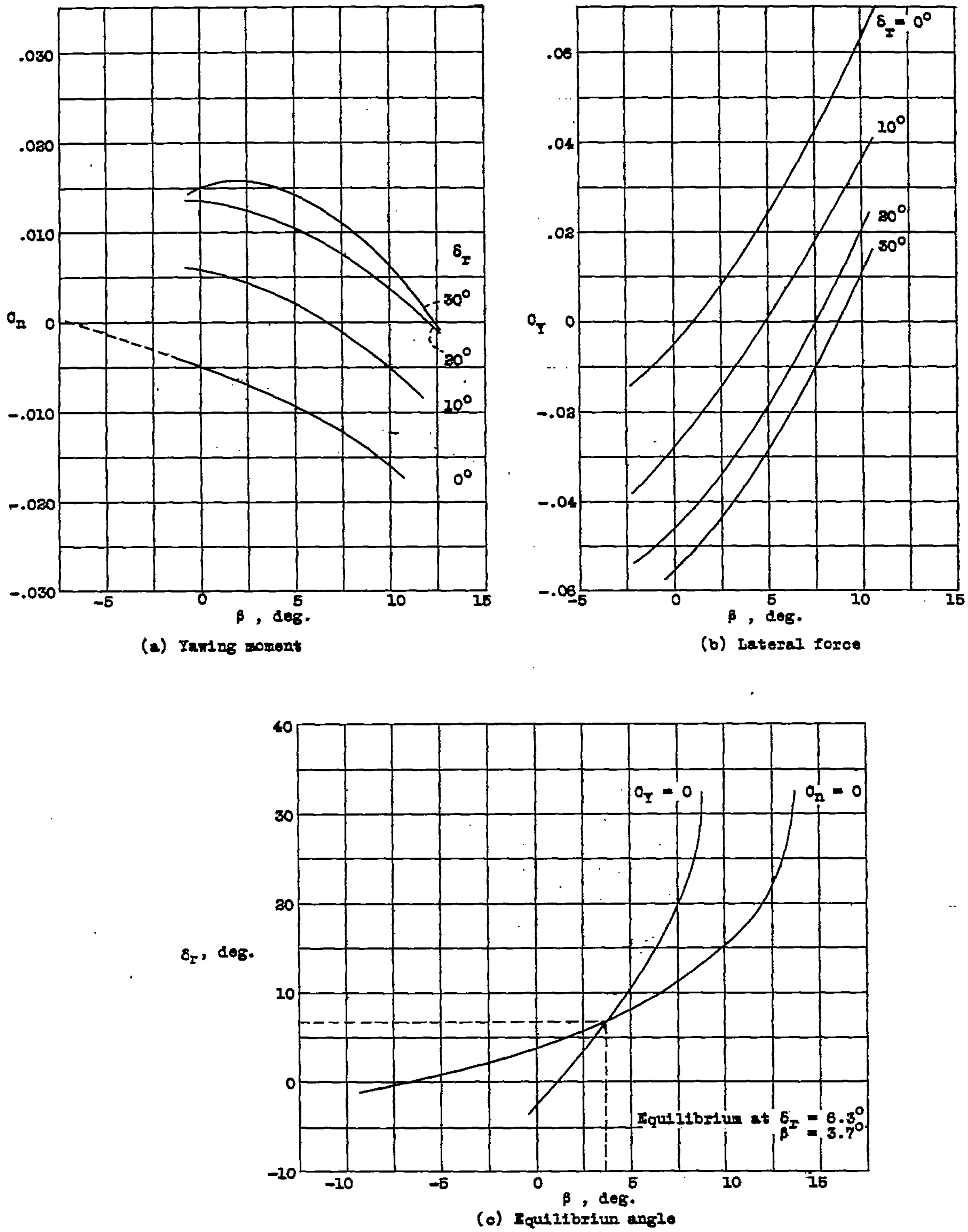


Figure 10.- Effect of toeing-out engines on airplane drag in normal 2-engine flight and on yawing moments after failure of left-hand engine. Full power on right-hand engine. Propeller hubs 48 inches apart.



(a) Yawing moment

(b) Lateral force

(c) Equilibrium angle

Figure 11. - Variation of force and moment factors with angle of sideslip. Left-hand engine dead; twin-rudder tail; α = 6°

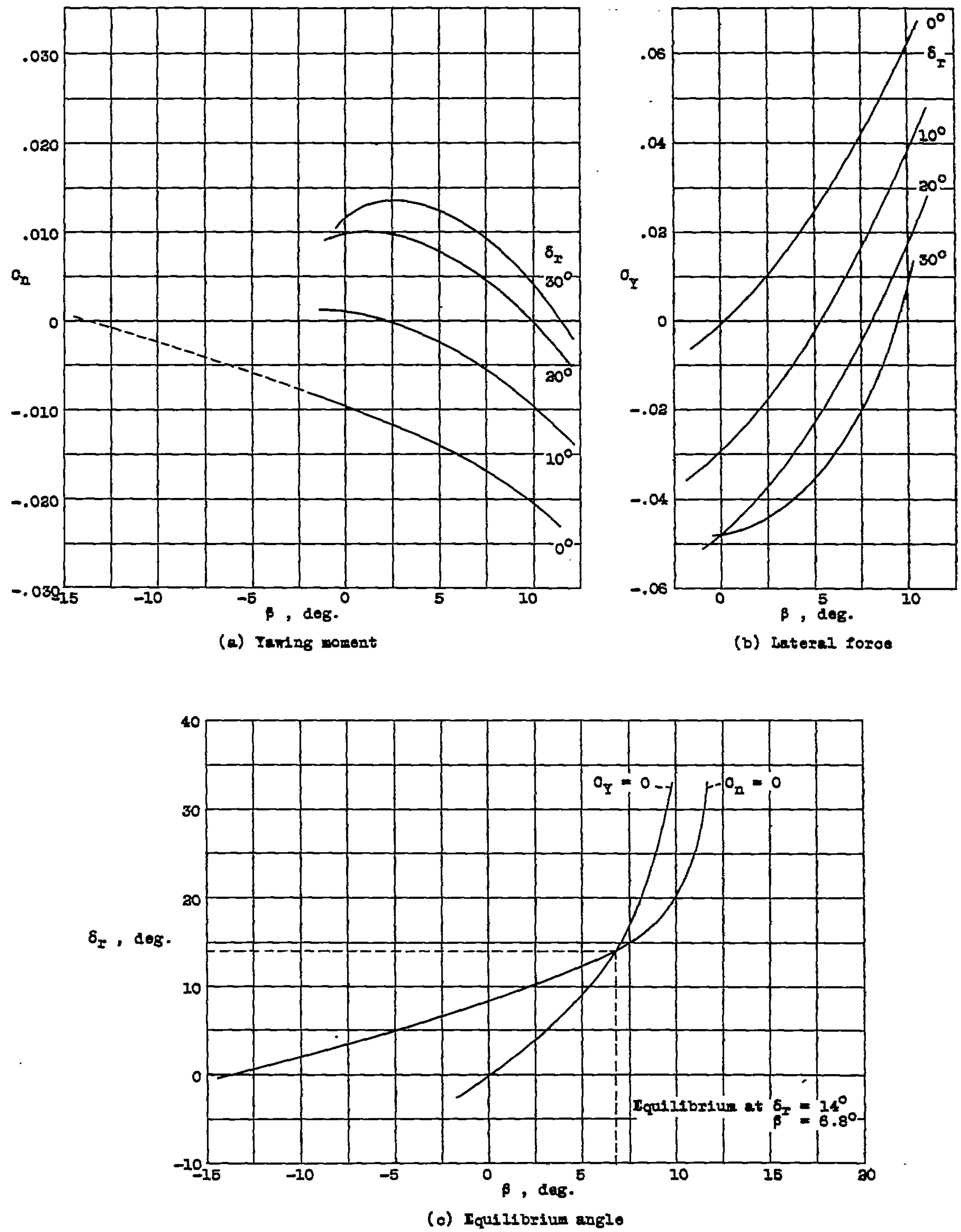


Figure 12. - Variation of force and moment factors with angle of sideslip. Left-hand engine dead; twin-rudder tail; $\alpha = 10°$.

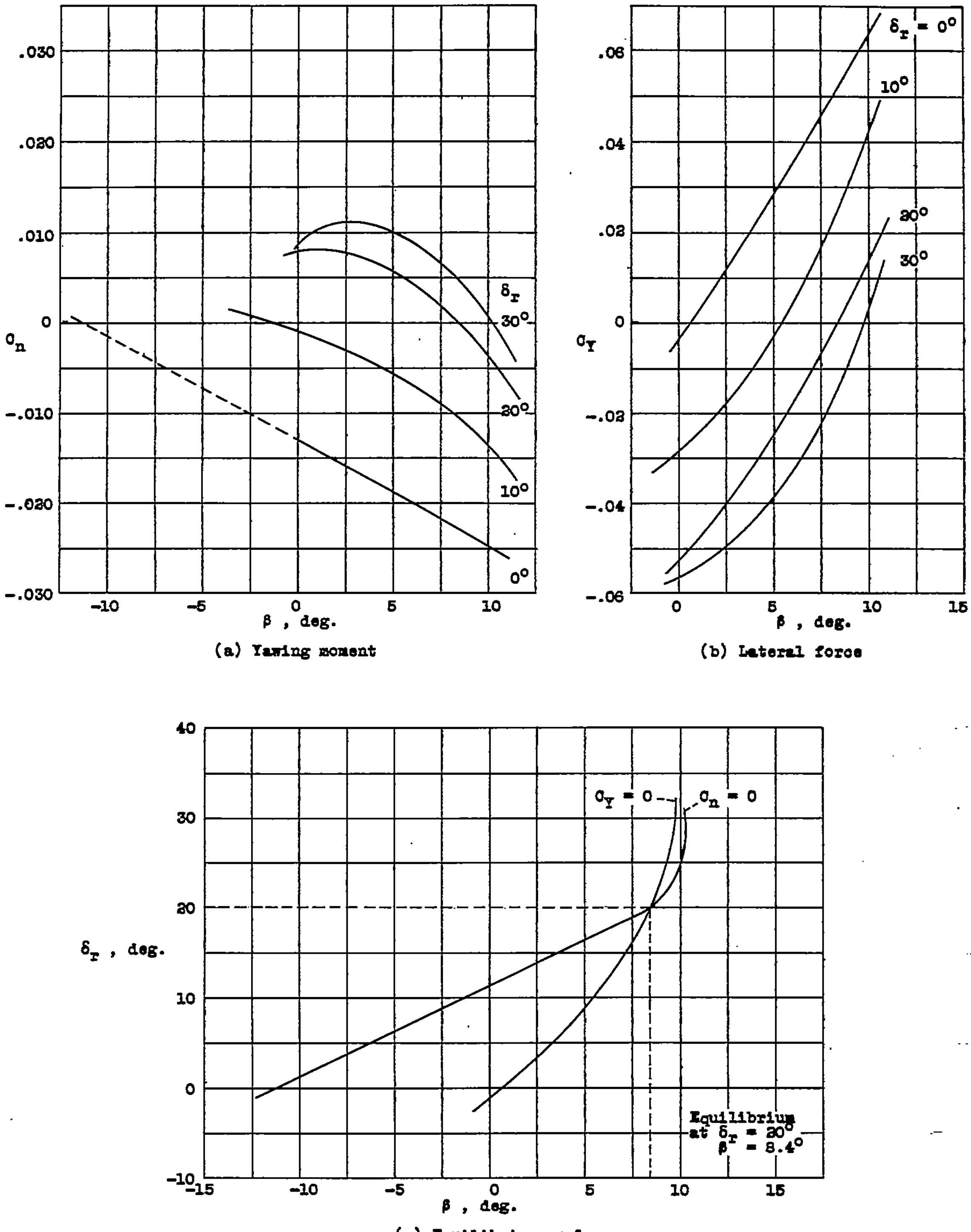


Figure 13. - Variation of force and moment factors with angle of sideslip. Left-hand engine dead; twin-rudder tail; α = 13°.

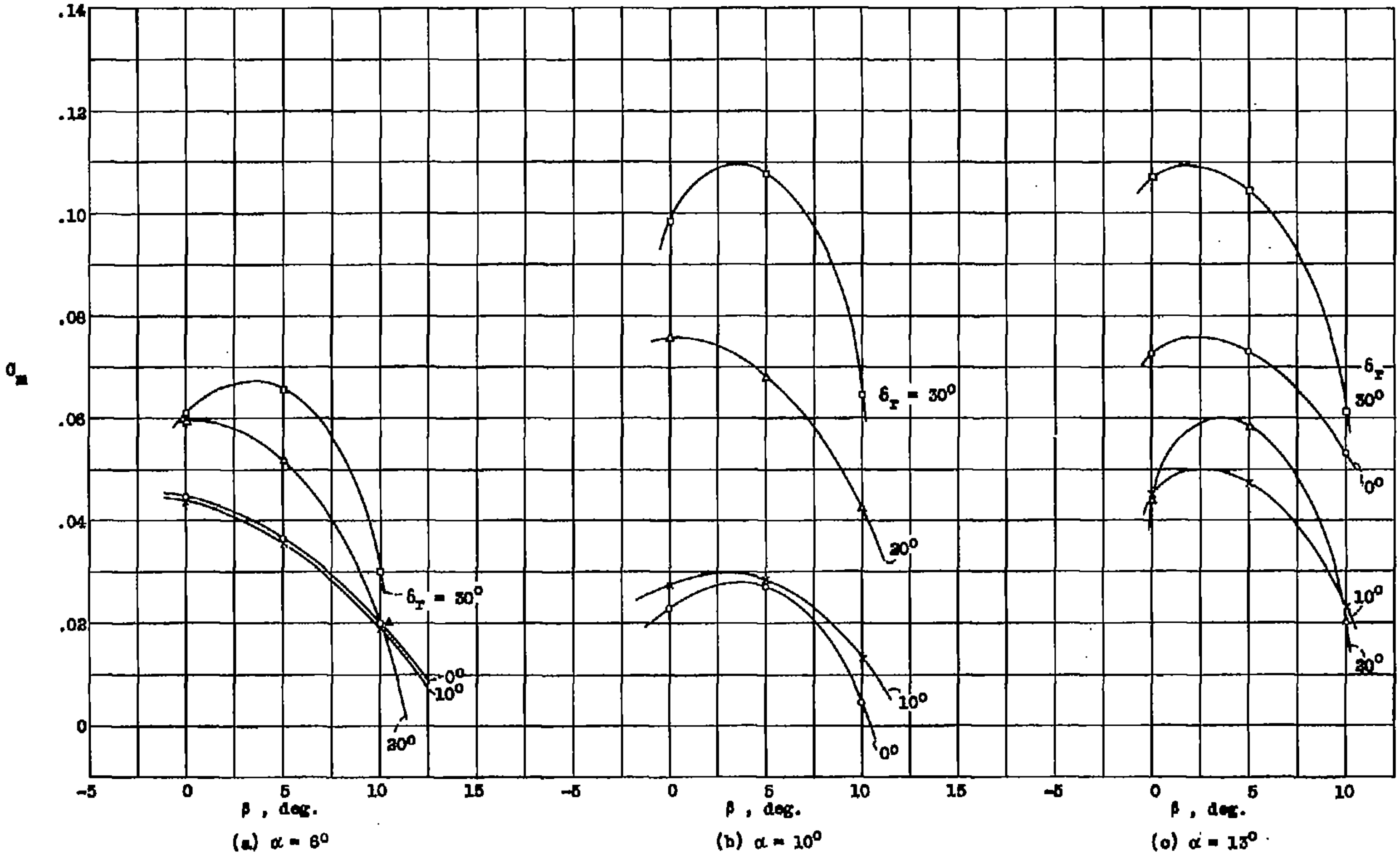
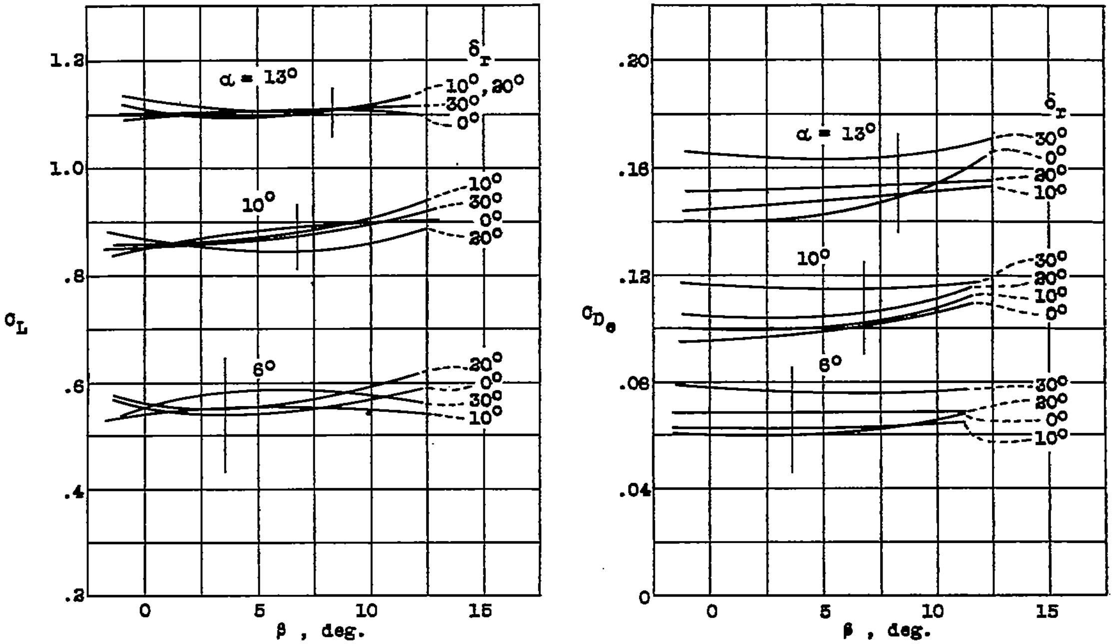
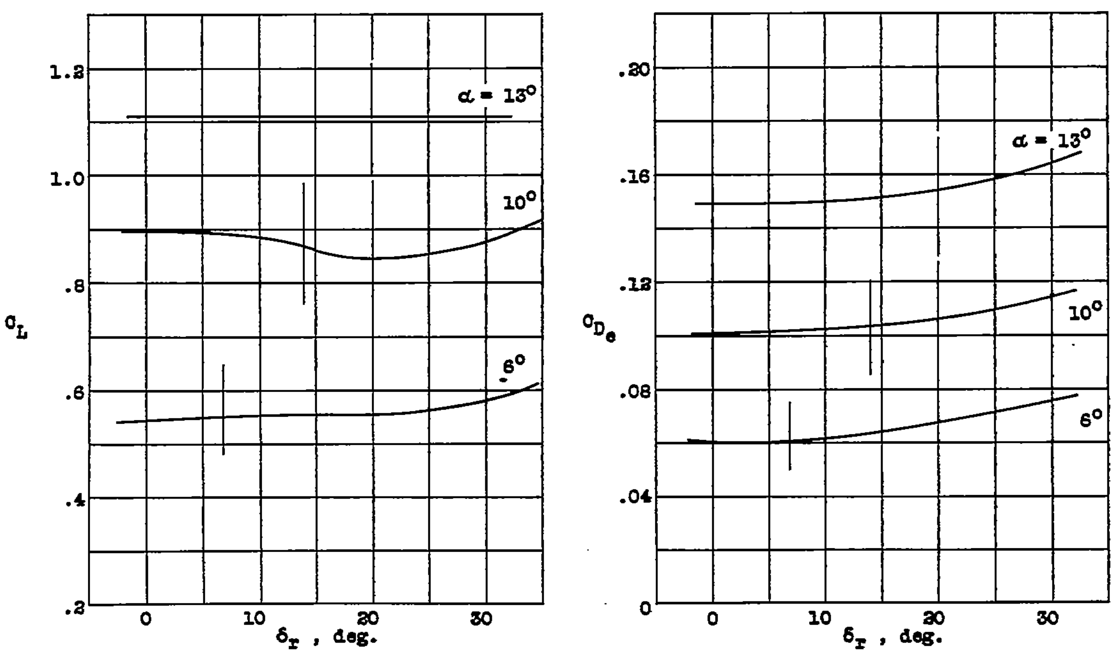


Figure 14. - Variation of pitching moment with angle of sideslip. Left-hand engine dead; twin-rudder tail.



(a) Lift coefficient.

(b) Drag coefficient.



(c) Cross-plotted lift coefficient.

(d) Cross-plotted drag coefficient.

Figure 15. - Determination of equilibrium values of C_L and C_{D_e}. Left-hand engine dead; twin-rudder tail.

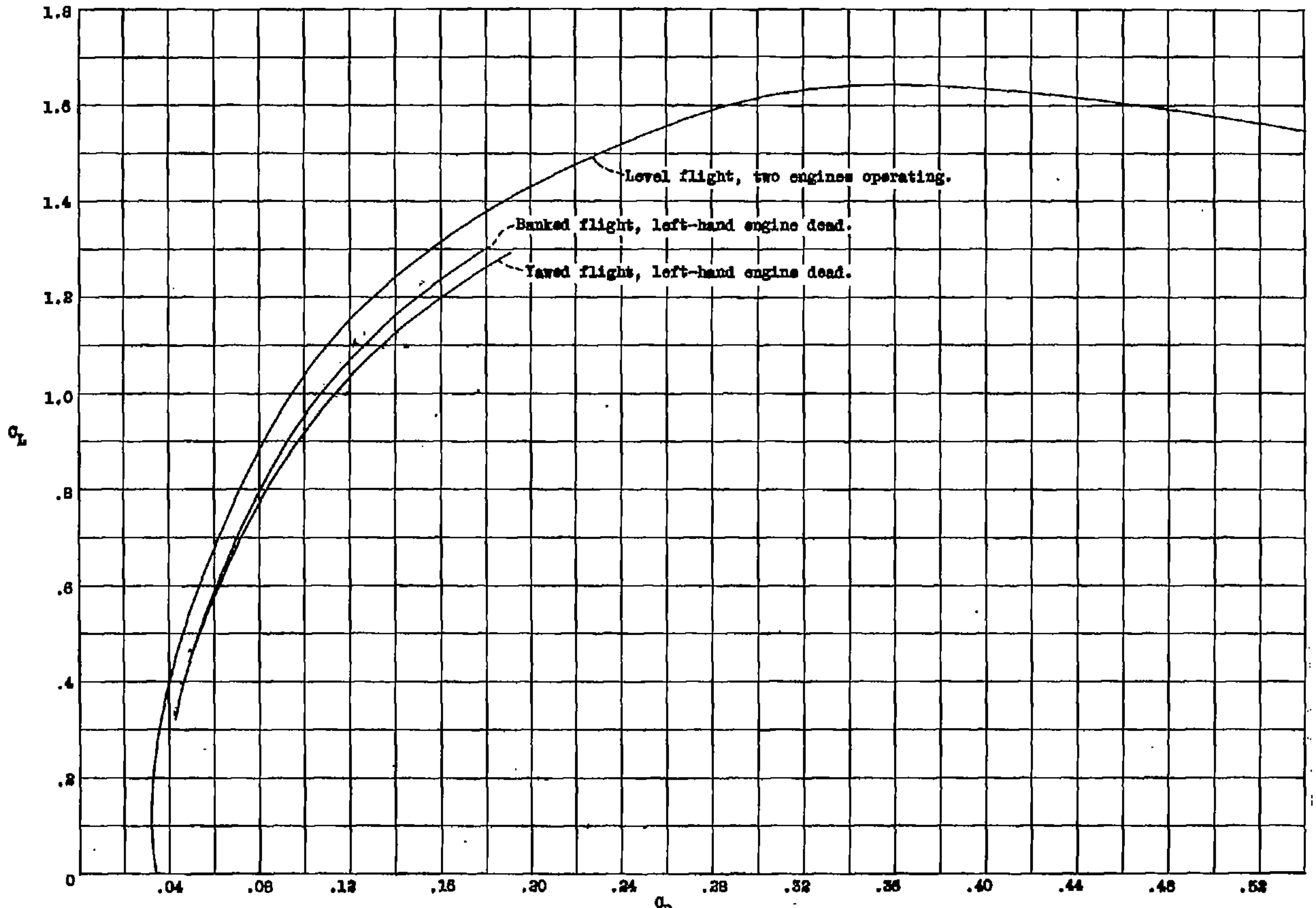


Figure 16. - Comparison of polars for two modes of flight on one engine and normal level flight. Curves are the same for both twin- and single- rudder tails.

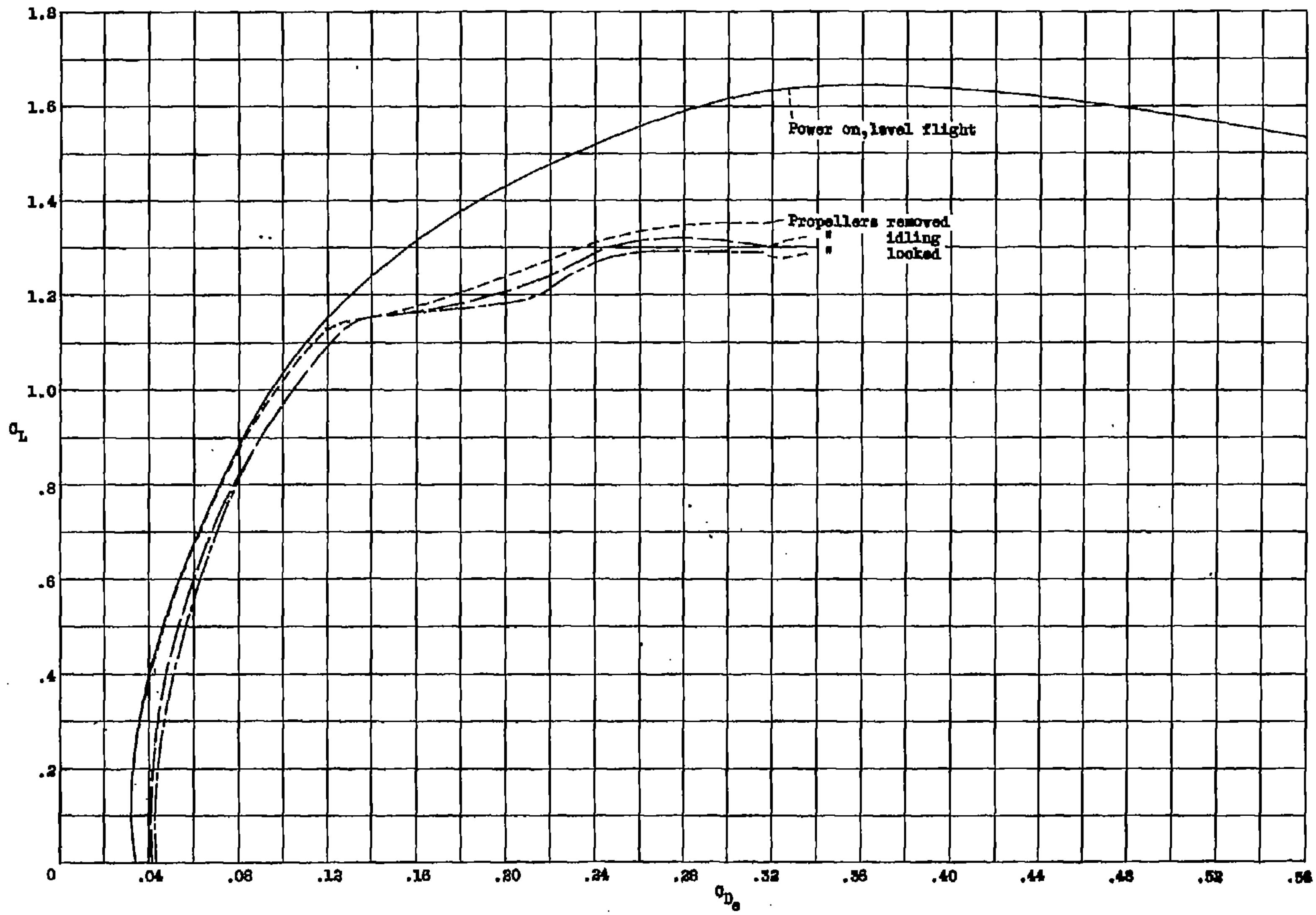


Figure 17. - Airplane polars for various propeller operating conditions.

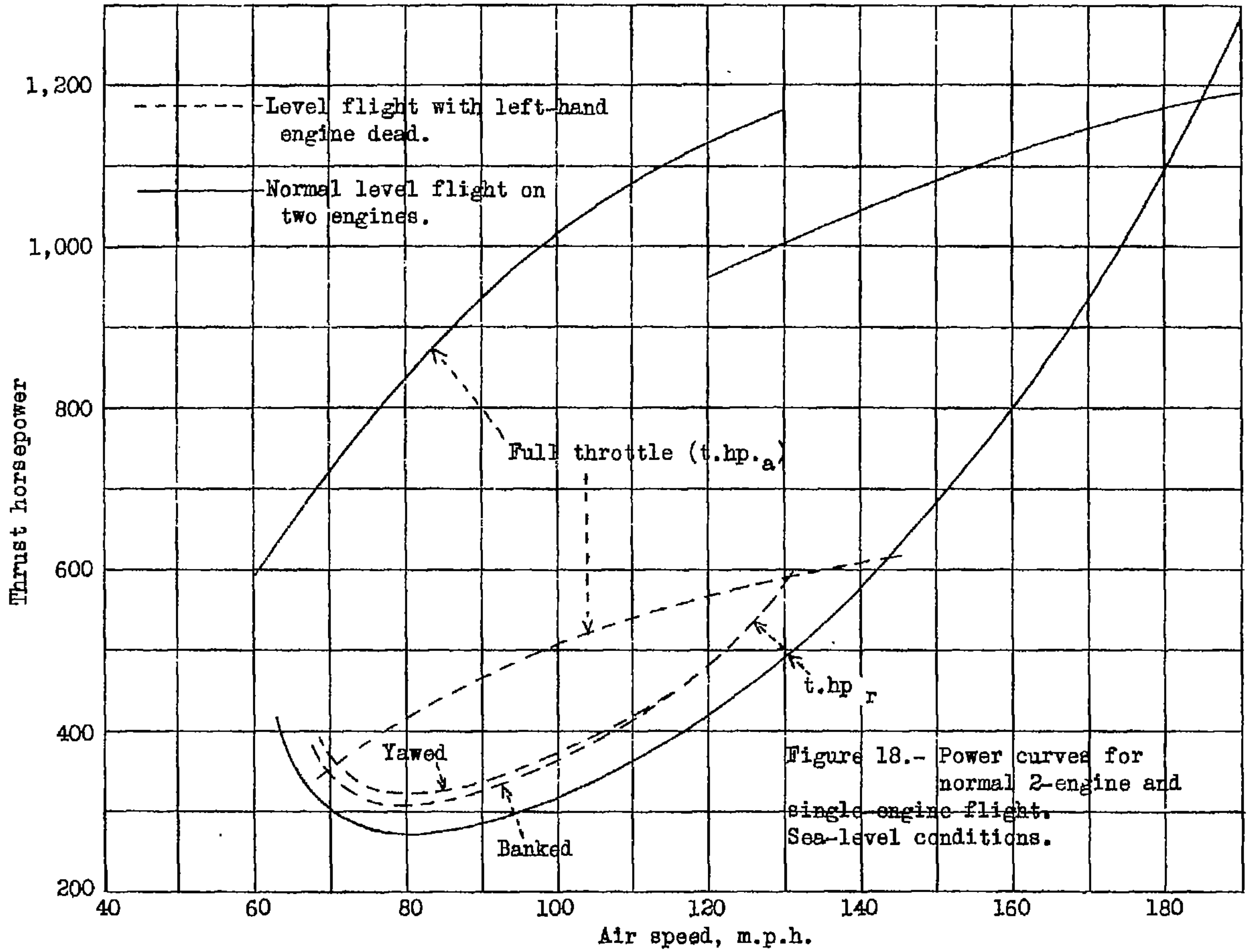


Figure 18.- Power curves for normal 2-engine and single-engine flight. Sea-level conditions.

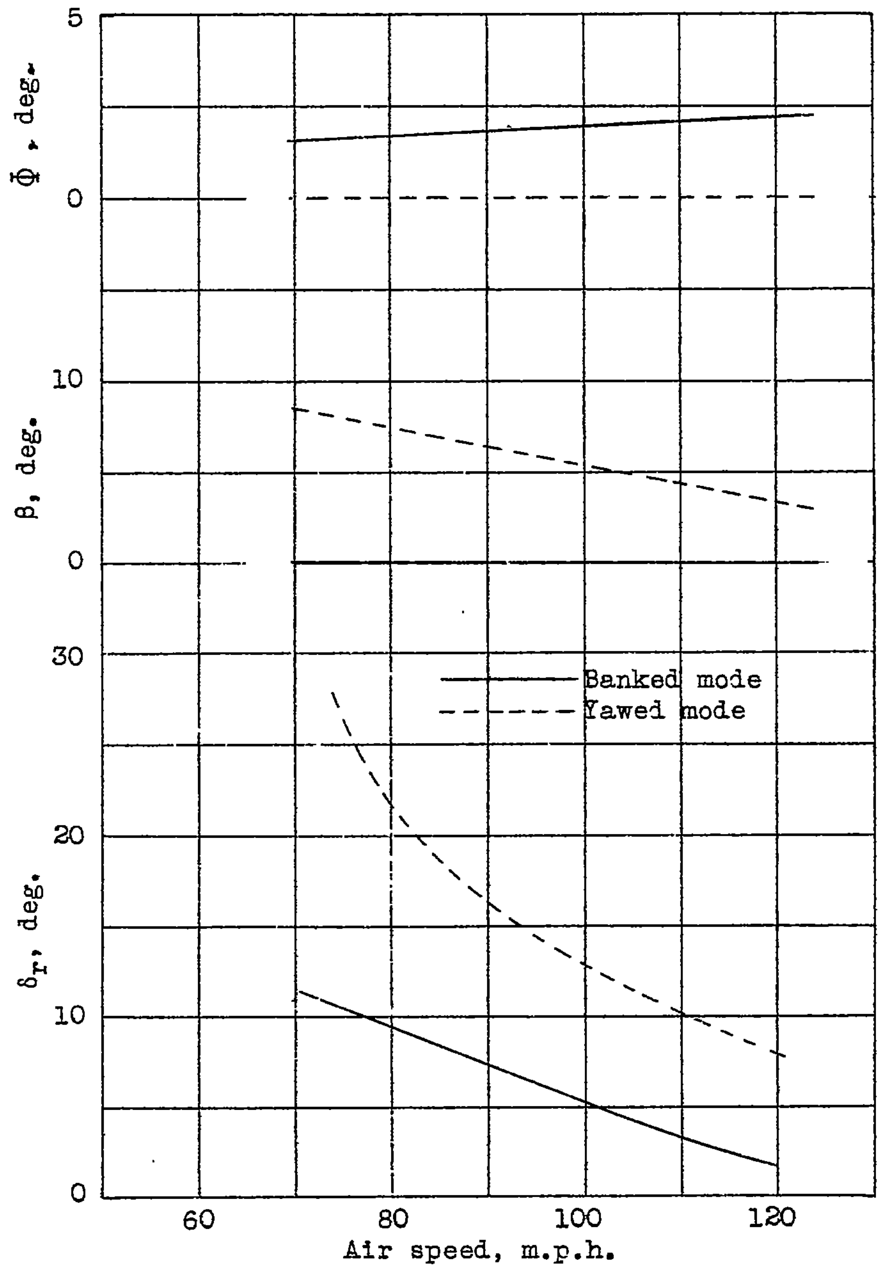


Figure 19.- Airplane and control angles for equilibrium. Left-hand engine dead. Single-rudder tail.

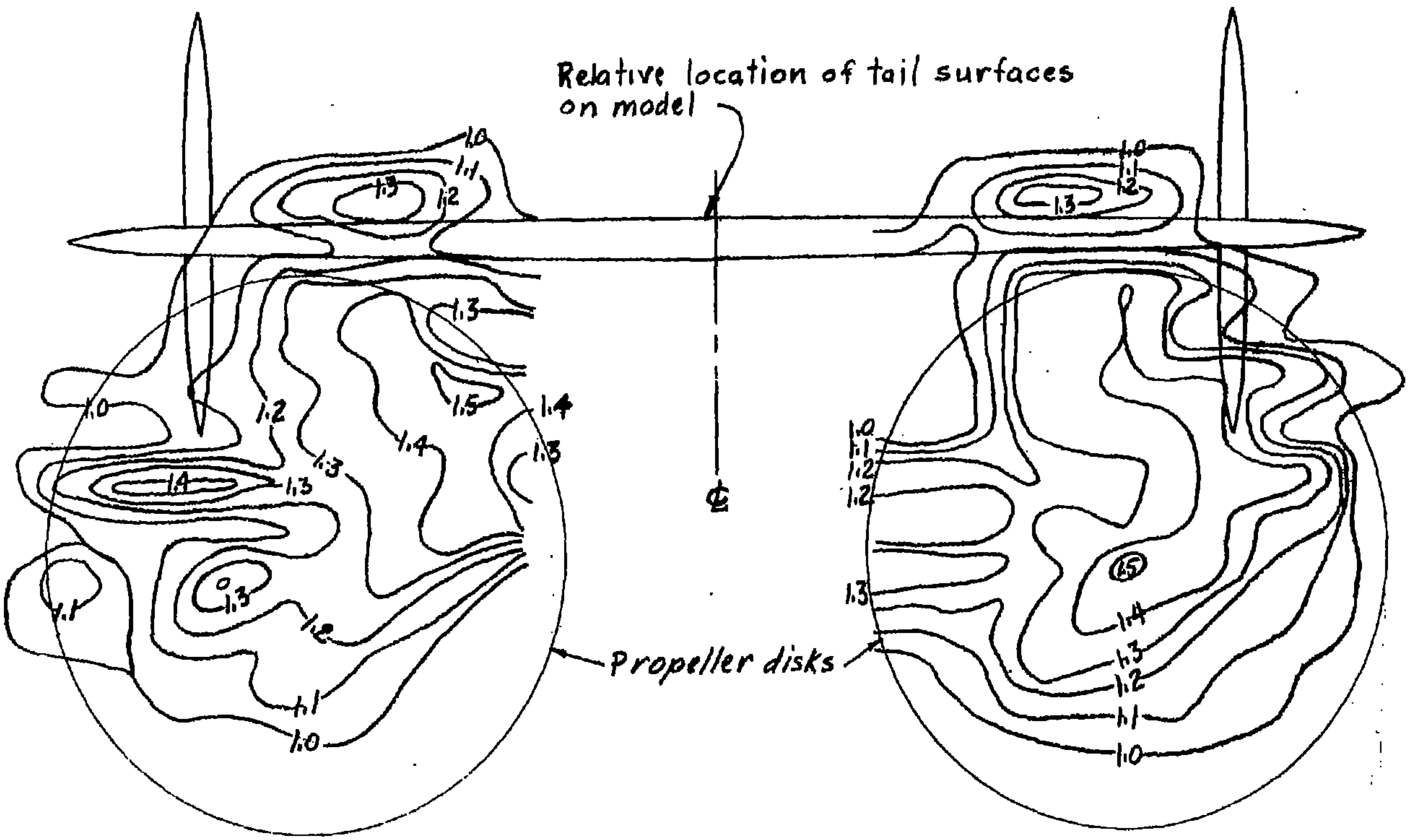


Figure 20.- Contours of dynamic-pressure ratio, q_s/q, in slipstream near tail.
View looking forward parallel to propeller axis.
(a) Angle of attack, 6°; $V/nD = 0.68$.

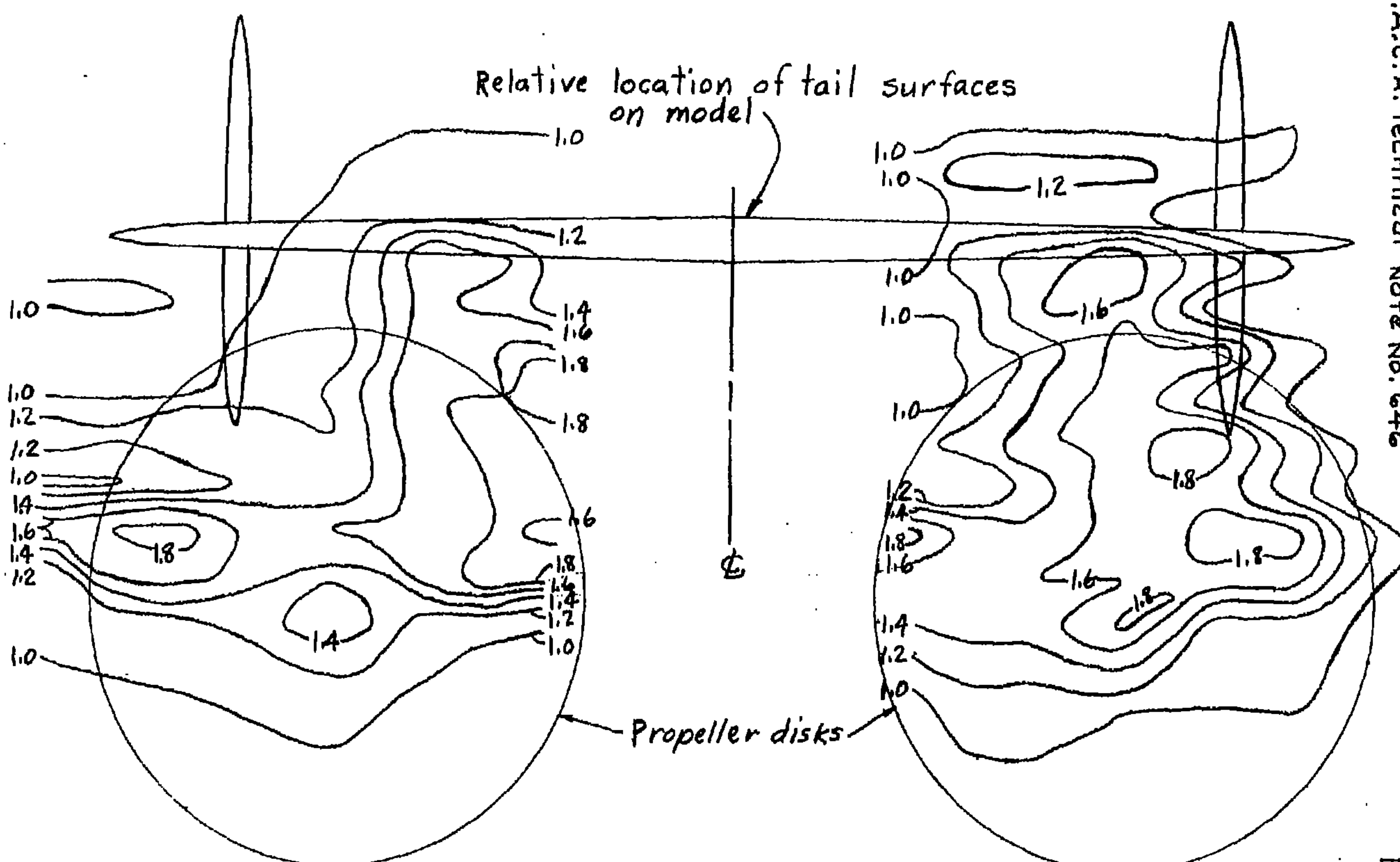


Figure 20- Contours of dynamic-pressure ratio, q_s/q in slipstream near tail.
View looking forward parallel to propeller axis.
(b) Angle of attack, 10°; $V/nD = 0.55$.

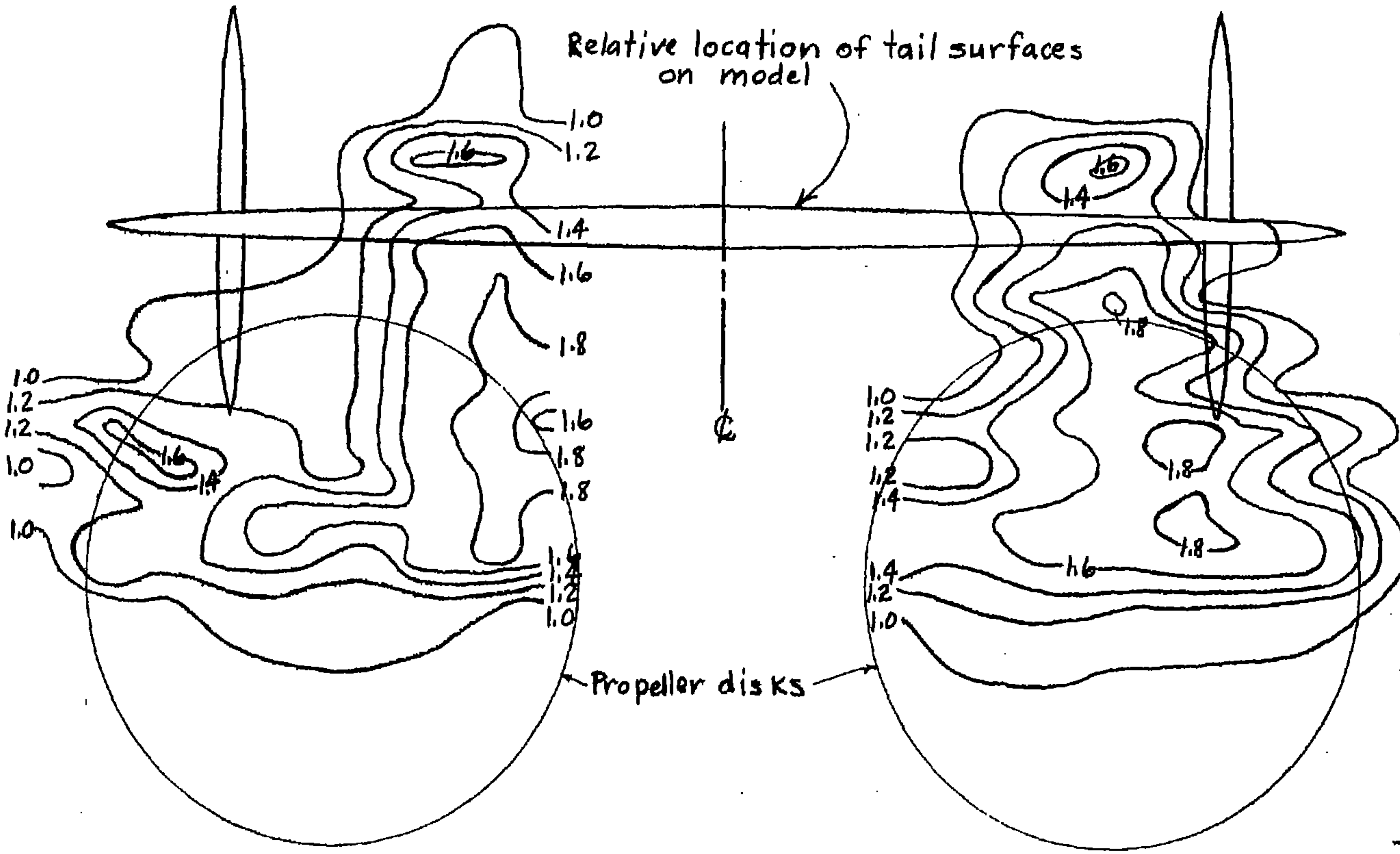


Figure 20.- Contours of dynamic pressure ratio, q_s/q, in slipstream near tail. View looking forward parallel to propeller axis.
(c) Angle of attack, 14°; $V/nD = 0.55$.

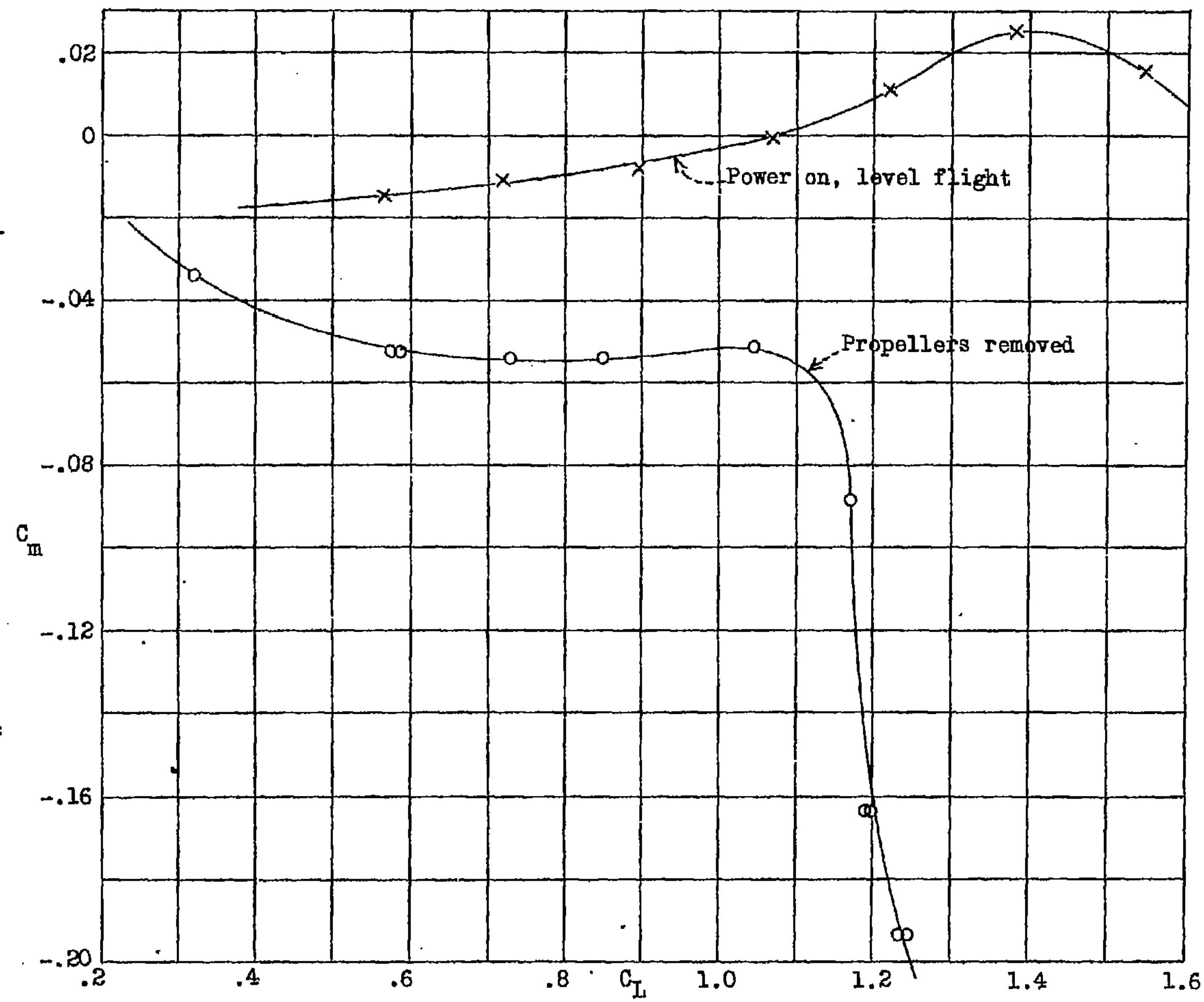


Figure 21.- Pitching-moment curves for airplane with power on and off. Single-rudder tail. Moment center at 27 percent of mean aerodynamic chord.

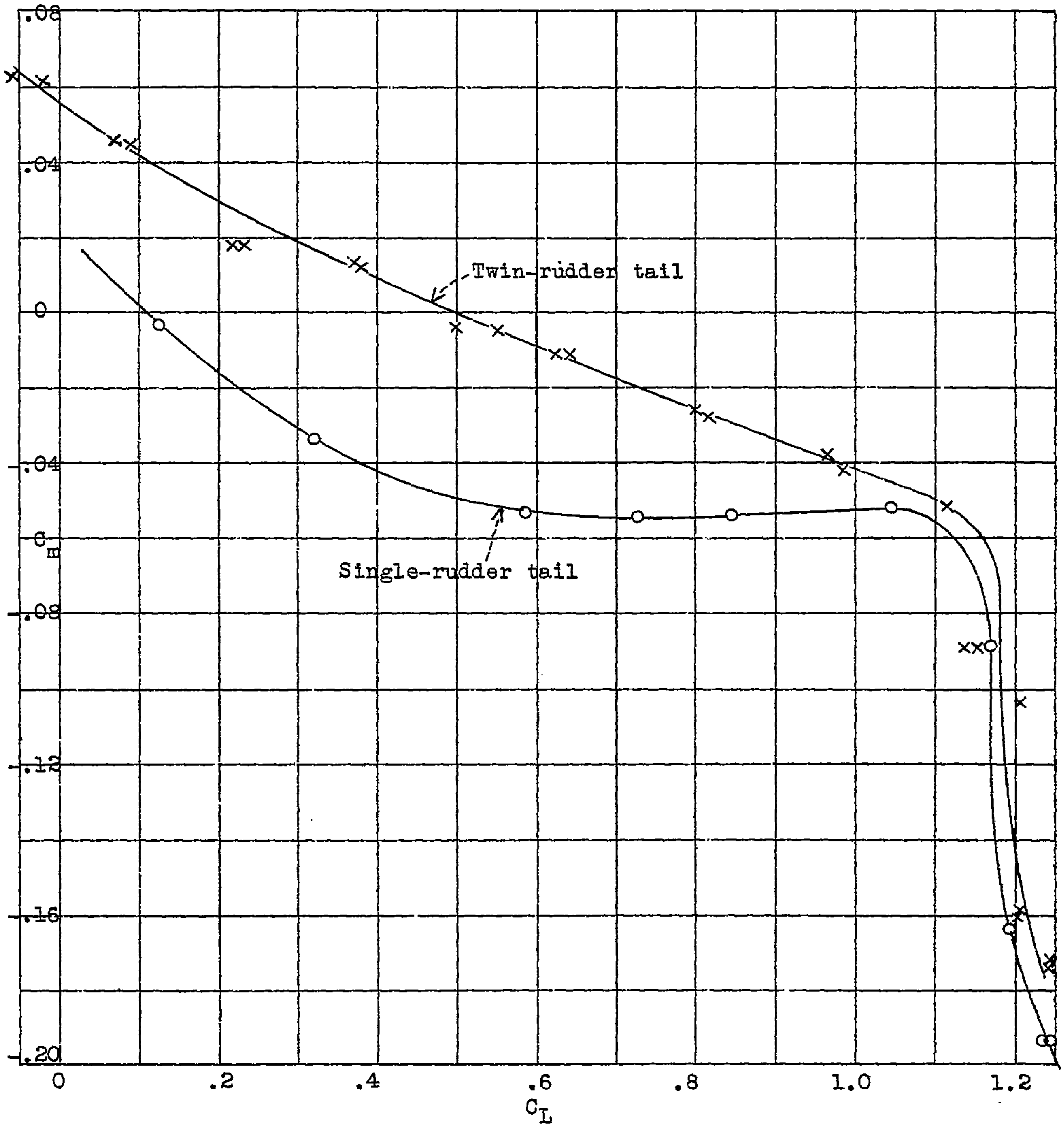


Figure 22.- Pitching-moment curves for airplane with two types of tail surfaces (See fig. 2). Propellers removed. Moment center at 27 percent of mean aerodynamic chord.

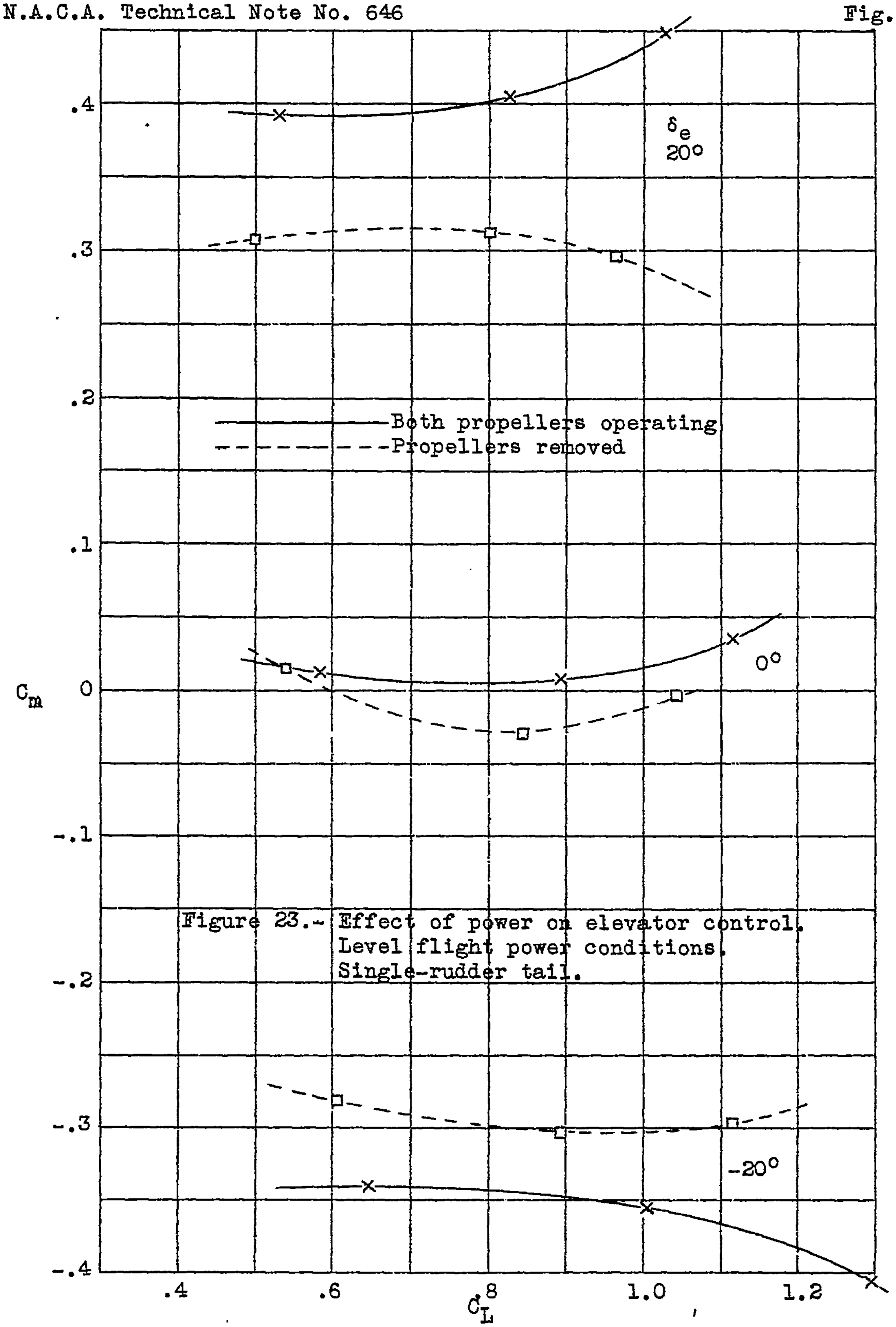


Figure 23.- Effect of power on elevator control. Level flight power conditions. Single-rudder tail.

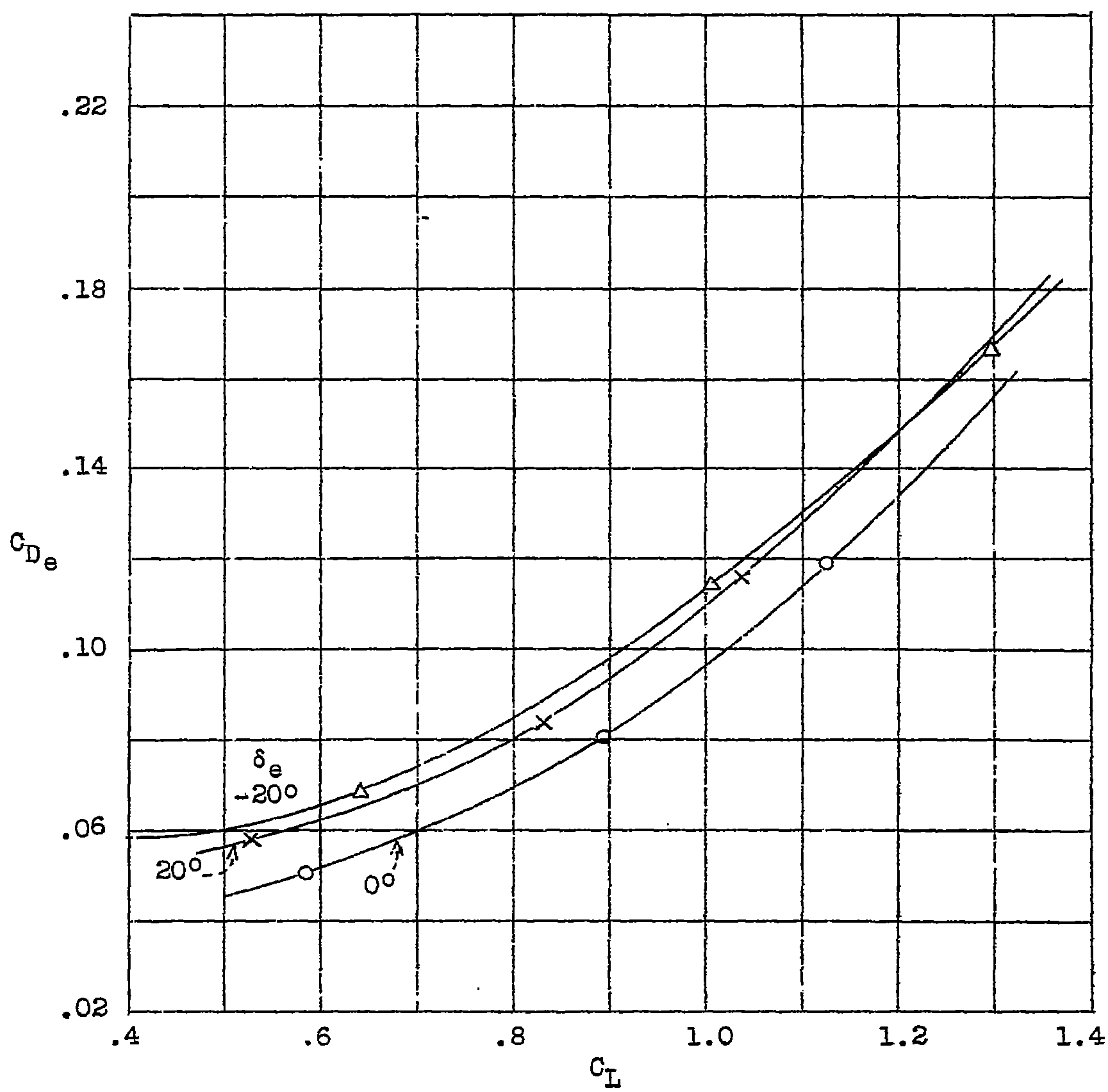


Figure 24.- Effect of elevator deflection on drag for level-flight power condition.

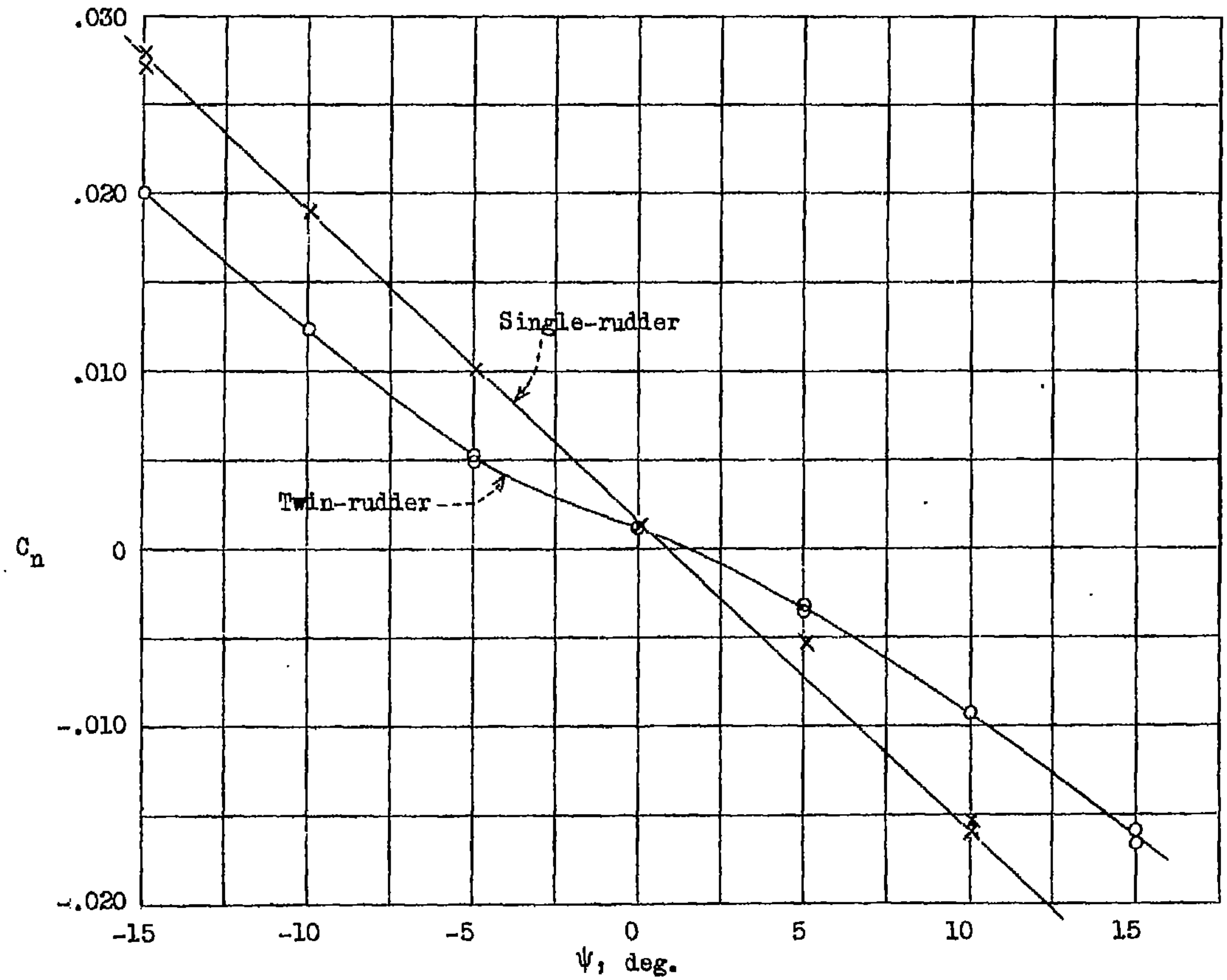


Figure 25.- Yawing-moment characteristics for single- and twin-rudder tails. (See fig. 2.) Propellers removed.

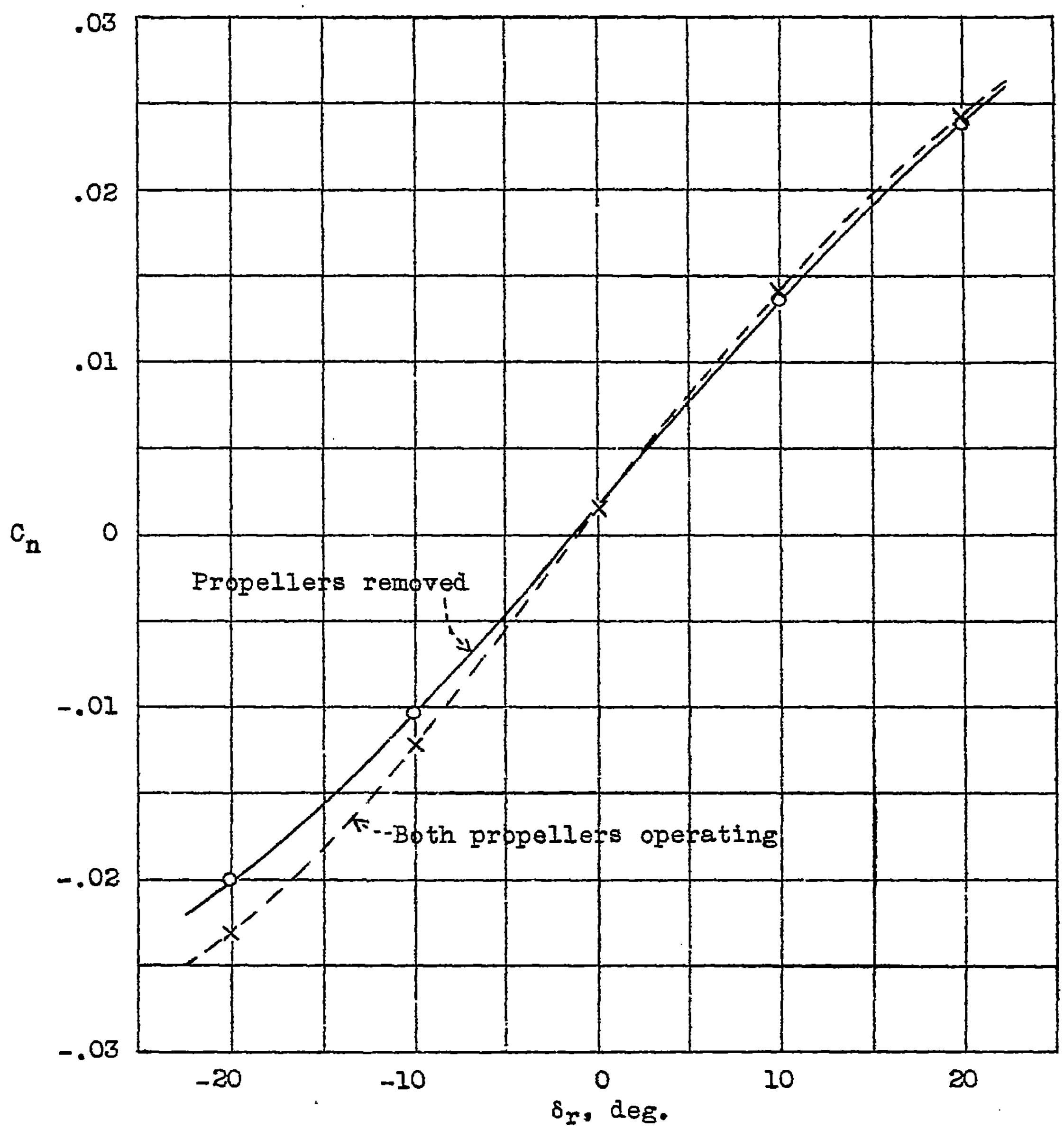


Figure 26.- Effect of power on rudder control. Single-rudder tail. Angle of attack, 10°. Level-flight power conditions.

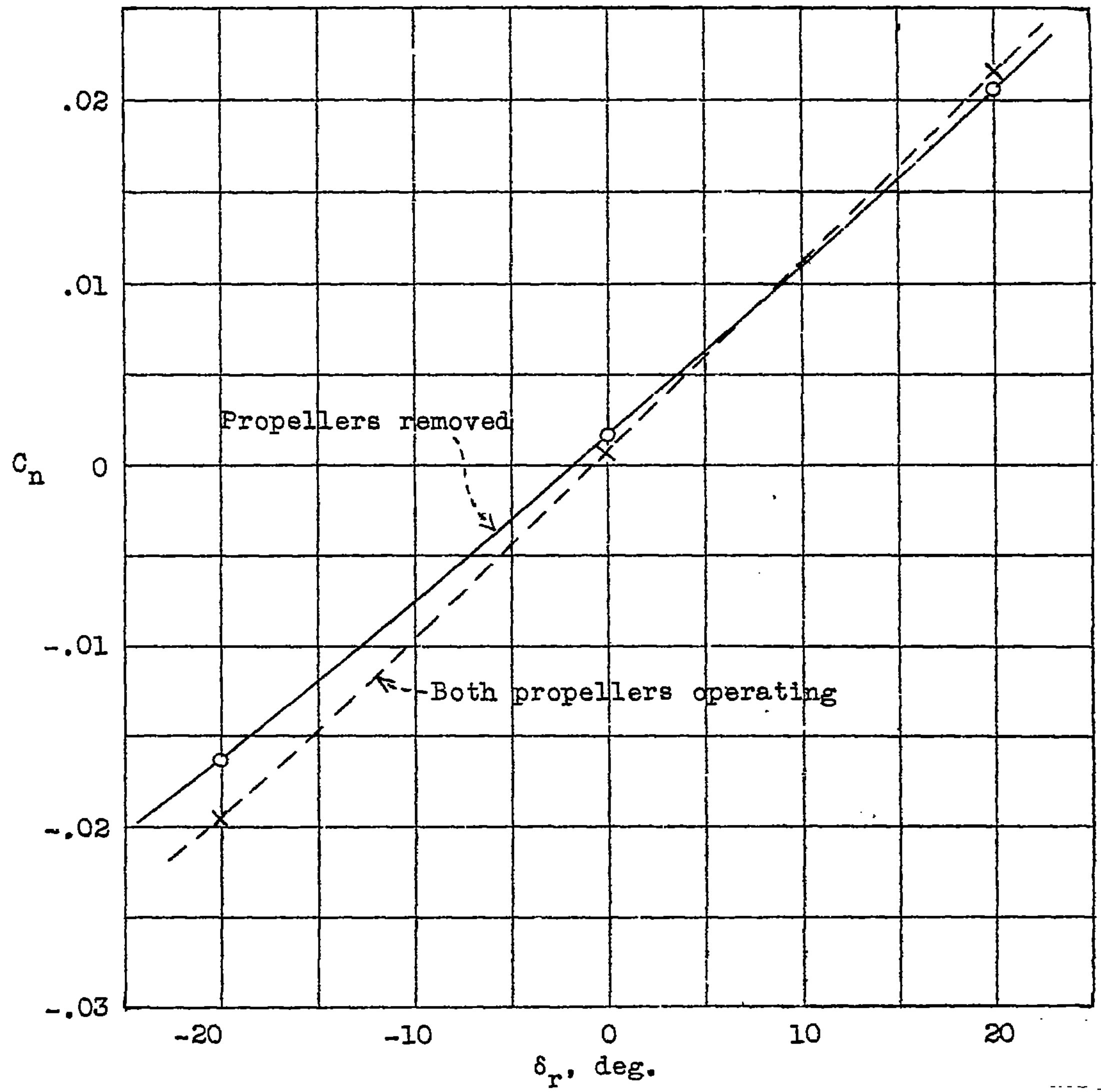


Figure 27.- Effect of power on rudder control. Twin-rudder tail. Angle of attack, 10°. Level-flight power conditions.